ISSUES AND STRATEGIES FOR IMPROVING CONSTRUCTIBILITY

by

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ABSTRACT

Constructibility is an attribute of a building's design, and is the most important attribute of the design during the construction phase of a building project. Building designs which are deficient in constructibility can severely affect both the monetary and time budgets of building projects. The avoidance of constructibility problems and the recognition and development of constructibility opportunities should be a significant concern of designers during each phase of the building design process.

This thesis responds to the research needs for future computerized design and construction applications by examining the specific concept of constructibility. It is addressed to knowledge engineers interested in providing tools for the design and construction of buildings. An understanding of the issues and context of constructibility is required to ensure that these future tools will be practical and beneficial in the real world.

The processes and players which make up building design and construction are examined in order to establish the context of constructibility. Definitions are analyzed and reasons for optimizing constructibility are discussed. The major issues of practicability, correctness, and clarity are proposed and constructibility problems and opportunities are categorized under these headings, with examples given from four case study building construction projects.

The "constructibility review" is discussed and shown to be inherently deficient as a strategy for utilizing constructibility knowledge. Finally, strategies and tactics for addressing constructibility during the design process are offered as alternatives appropriate to the capabilities of CAD and KBES, and the needs of designers.

Thesis Supervisor: Jerome J. Connor
Title: Professor, Civil Engineering Department

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INTRODUCTION

This thesis is a response to the need for an understanding of the concept of constructibility. Such an understanding is essential to knowledge engineers who are interested in providing design tools for the building construction industry. Ibbs[1], in reporting on a research workshop sponsored by the University of Illinois Construction Engineering and Management Program and the National Science Foundation in May of 1985, which discussed the crucial research needs for future computerized construction applications, reports that:

> "An important issue in the minds of many was the identification of the characteristics of the information itself and the information flow between project team members. These attributes should be studied to determine the content and relationship between the elements. It was pointed out that the construction industry, while now highly fragmented, will probably change in structure to allow greater integration. The necessary standards to achieve integration definitely need research and development.
>
> "An underlying prerequisite for the development of such standards (preferably voluntary guidelines) is a greater understanding of the data requirements and cognitive processes in each phase of the design-construct cycle..."

Constructibility is the attribute of a building design which is of most importance during the construction phase of a

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[1] C. William Ibbs, "Future Directions for Computerized Construction Research," Journal of Construction Engineering and Management Vol. 112 No. 3 (September 1986): p. 330.

building project. Building designs which have constructibility problems can be the cause of time delays, budget problems, lawsuits, and in the worst cases, project bankruptcy. Likewise, designs which fail to benefit from constructibility opportunities cause construction to cost more than it should. Constructibility is a practical aspect of a building design, and as such, must be addressed by knowledge engineers if their computerized design tools are to be of practical use.

The concept of constructibility can only be fully understood in relation to its context. Thus, we begin this thesis with a description of the processes and players which comprise building design and construction. After we paint this background, we will discuss the concept of constructibility, some definitions, major issues, and develop categories of generic constructibility problems and opportunities. We will present actual examples of each constructibility category from four case study construction projects. Later we explain how such examples may be a valuable source of constructibility knowledge.

Finally, this thesis will propose some strategies and tactics by which we might optimize the constructibility of building designs. We also will discuss some sources for constructibility knowledge which will be helpful to knowledge

engineers as they attempt to acquire the knowledge to incorporate in the tools that we hope will be created.

Impetus for Research

Before coming to M.I.T. I spent two and a half years as a construction contract manager/administrator in the office of the Resident Officer in Charge of Construction at the Naval Air Station in Brunswick, Maine. During that period I administered approximately $13 Million worth of construction. Prior to that job I trained for a year as an intern architect under the direct supervision of registered architects. As an intern I worked on the design of numerous buildings and their detailed construction drawings. These three and half years of experience in building design and construction have given me insight into the issues of constructibility, and the potential benefits of the optimization of the constructibility of building designs.

While in the architect's office I struggled with the design of routine details, and even the task of selecting the location of drawings on the page. Not yet having been exposed to construction practices and techniques, I relied heavily on Architectural Graphic Standards and picked the brains of the other architects in the office for guidance and advice.

Although I was drafting on the latest version of a Computervision CAD system, I effectively had as my design tools only an electronic pencil, a screen, and an electronic T-square.

One of my responsibilities as a construction contract manager was to perform "constructibility reviews" of designs which were going to be advertised for competitive bidding. As I gained construction experience, I found that my constructibility comments increased in number and specificity with each review. I was determined not to allow designers to make me suffer through their repeated mistakes. However I had very little time for this review, because active contracts were so demanding. Consider the $7.5 Million contract for the construction of an Operations Control Center, just one of several contracts I controlled. On the Control Center job alone there were in excess of 125 change order items and 150 field changes[2], a large majority of which were due to inaccuracies or inadequacy of the design documents. How could I try to prevent these problems if I had to spend all my time solving them?

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[2] Change orders are changes which involve a modification to the cost or time of a construction contract. Field changes are changes to the design which are necessary but do not affect the cost or schedule of construction.

Who is Responsible for Constructibility?

It was obvious to me by the time I left the construction manager position that the constructibility of building designs was regarded as the responsibility of the construction manager/contractor team. Many designers, (especially young ones like myself), had little experience with the realities of the construction process or construction techniques. Why were we being allowed to prepare construction documents?! It was in answering this questioned that I sensed a shift in the meaning of the word architect away from master builder and toward artist/space planner/color-and-finish-picker. The construction documents of most buildings were being prepared by people trained in subjects foreign to construction. As designers, we were in fact contractually and professionally isolated from constructors. When I applied for permission to take the architects' registration exam, I unbelievably discovered that experience, (three years is required), gained under the supervision of registered architects was disallowed if it was gained in a company that also performed construction!

There were of course many very "construction wise" architects that I met and admired. They were the ones that were regarded as "knowing how to put a building together". The funny thing was, they were not regarded as the best architectural

designers. This status was given to the imaginative space planners and artistic designers who could capture in pastel chromatics the essence of the Parthenon, the Pantheon, and the intermundial plain, and produce a public restroom that would elevate your consciousness to levels as yet not imagined by the common man. The translation of these work-of-art sketches into construction documents, however, was neither one of their better skills or interests. When the translation was subsequently performed by others, it was apparent that much of the effect was lost and there resulted just another cracked tile, urine-odored room, whose only uplifting character was provided by the sneak who occasionally graffitied some very witty and wise epithet upon the water stained pastel wall.

The Great Ones

We must admit that the great engineers were very artistic and that the great architects had a very profound understanding of the technical aspects of their trades. Mies found God in construction details, and Brunelleschi held up the heavens of the great dome of the Duomo in Florence with a system of horizontal and vertical ribs coupled with a dual shell which he, a goldsmith by trade, designed and constructed. It so affected the skyline that it gave birth to Renaissance Architecture. The great and innovatively successful bridges

are all beautiful to the eye, not just the monotonous resultant of some mathematical formula. The "great ones" had an understanding of the physical limits of materials and their associated construction techniques which allowed their imaginations to stretch the envelope of those limits. Only this understanding can guarantee that the built form does become the work of art that it was envisioned as and meant to be.

Can We Be Great?

I would propose that if architects and engineers had modern day design tools, such as expert systems and knowledge bases of pertinent information, they would more readily and accurately produce the great designs expected of them. All of this pie in the sky has been proposed before, but now we are seeing new and practical applications of the concept being used in and developed for commercial markets. Routine design is being optimized in terms of cost of design production as well as physical construction and operation. The T-square is no longer the only tool available to designers, and long years of valuable experience are remaining in firms in electronic form despite the retirement of the person who acquired it.

I hope to contribute in a small way to the possibility of our

potential collective greatness by revealing the issues of constructibility and suggesting strategies by which they can be most effectively addressed. In the future I hope that more and more great design can in turn be produced which is imminently uplifting and optimally constructable.

CHAPTER ONE - THE CONTEXT OF CONSTRUCTIBILITY

Introduction

The purpose of the first part of this thesis is to obtain a basic understanding of the context of constructibility. The concept of constructibility is basically concerned with the relationship between the design and the construction of a building.[3] Therefore it is best that before we attempt to understand constructibility, we should understand the basic organizations, relationships, and processes involved in building design and building construction. After we have a clear picture of this context we will begin to develop an understanding of the meaning and importance of constructibility.

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[3] This thesis is primarily concerned with building design constructibility. We acknowledge that the designs of other structures also have a constructibility attribute. We also agree with the Constructability Task Force of the Construction Industry Institute that procurement and construction management practices can have a constructibility attribute. The constructibility issues and categories developed later in this thesis are based primarily on building design, but may be applicable to other domains.

Building Design

The Building

The root of the relationship mentioned above is the building. For thousands of years our species has been designing and constructing buildings in order to provide shelter for human activities. Beginning probably with a simple roof and walls for protection from the weather, we have improved our skill to the point where we can now provide super clean environments for the manufacture of the most sensitive computer chips. Our cultural history has been expressed in and influenced by the buildings which we have designed and built. The Greek temples for the gods at Athens and Agrigento, the palaces of Louis XIV, and the monuments to modern industry as expressed in corporate headquarters like that of ATT in New York City, are much larger than life but essential to it. They are monuments to our ability to work together, to combine the efforts of our minds and our hands in the production of something that we could not do alone.

The effort expended in the realization of a building can be divided into the two relatively distinct processes of design and construction. Design and construction both require order, i.e. a process, and a team of players to perform the process.

Since design is necessarily the predecessor of construction, we will begin our study with an investigation into the process and people that combine to give us a building design.

Design

To begin, let us establish what we mean by design. Basically, designing is planning a response to a certain stimulus. The nature of the stimulus determines the outcome of the process. Early man designed a hut because of his need to protect himself from the elements. The surgical laser scalpel was a response to our specie's care for each other as manifested in the medical profession. A design is simply the product of one who designs. It is a description of the planned combination of real objects, that when actually combined, will serve a specific purpose. The purpose of the design is to guide the actual combination of real objects.

A design may consist of drawings, physical or computerized three dimensional models, written specifications, or any other DESCRIPTION in any vocabulary or language which the designer determines to be most useful for conveying his ideas. Indeed, the designer may produce a design for something by manipulating thoughts and images within her own mind, thus producing a design to which only she has access.

Fundamentally then, to design means to create a description of something in response to a certain stimulus which will serve a predetermined end, which can be used to guide the actual creation of that something.

The Design Process

The design process is the same no matter what one is designing. It is commonly represented by the model shown in figure 1.1.[4]

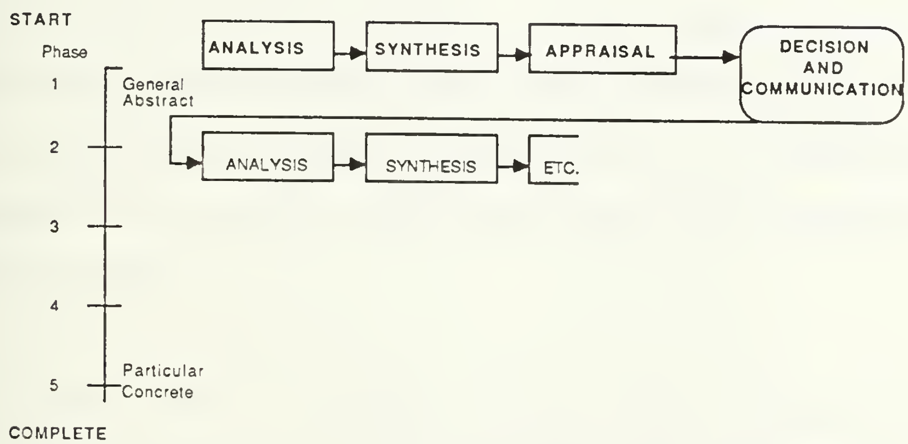

Figure 1.1 The Basic Design Process

[4] Markus, T. A., ed., Building Performance, (New York: John Wiley & Sons, 1972), p. 22.

The design process consists of three parts. The first part is ANALYSIS, in which the designer contemplates and comes to understand the problem. Once the problem is understood, the designer begins SYNTHESIS, i.e. he produces a description of a solution to the problem. Finally the designer performs an APPRAISAL in that he establishes the performance of the solution. The process results in a decision which is communicated. In Genesis the Lord realized that he was lonely and that he needed something to keep Him entertained (Analysis). He envisioned the heavens and the earth (Synthesis). They were created and the first day ended and the Lord looked at his creation and said that it was good, (Appraisal). The Lord repeated this process for six days until his loneliness was solved. In the same way, any designer will repeat these three steps as many times as it takes to create an adequate description of an acceptable arrangement of elements, which when built will satisfy the problem at hand.

Of course the model is simple but the actual process itself is not. It is interesting to note though that the model is basically a decision model for problem solving. Every moment of every day we encounter stimuli which make us analyze, synthesize, appraise, and decide on our response to each stimulus. It is important and comforting to realize the simplicity of the basic design process, as we attempt to

tackle a very complex instance of it, that being building design.

The Building Design Process

A building is a physical entity familiar to all of us. It is a man made structure that protects and encloses the space required to accommodate a particular function. The particular function to be accommodated, along with the site and socio-economic context within which the building is placed, are the ultimate determinants of the final physical construction of the building. If the function of the building is to provide an environment where the business of banking can thrive, the building will be composed of spaces and environmental control systems different than if the function of the building was to provide an environment where chickens can lay eggs. The place and the purpose of the building is information critical for beginning the design process.

As a reference for our study we might keep in mind a typical office building. We can assume that the building accommodates people and business machinery such as mini and personal computers. Within the building are large offices for groups of workers, private offices for company officers, lunch areas, restrooms, large conference areas and small meeting rooms. We

can envision three or four businesses of between 25 and 50 people each, occupying the building.

Building Design - Descriptions for Construction

In order to make decisions about and to direct the materialization of a site transformation, designers generate descriptions of the building. Many types of description exist, the most common being orthographic projection drawings (the familiar blue prints: plans, elevations, sections, and details), written specification documents, and three dimensional physical models of cardboard and balsa wood. Other descriptions include computerized databases, building requirements programs, design briefs, rendered perspectives, and even construction plans and schedules. These descriptions are usually grouped by building system. Each type of description helps people solve relevant problems. Usually a diverse set of descriptions is required in order for the physical transformation, the construction of the building, to take place. All of the descriptions ultimately serve to facilitate the physical construction of the building.

Design Description Sequences

The descriptions of a building evolve over the course of the design process from being very general to being very specific. This description evolution has traditionally been divided into distinct sequential phases based on the relative level of detail expected in each phase. This sequence of phases is familiar to architects and engineers as the phases defined in their design contracts, and is shown in figure 1.2. An expanded description of the design phases is provided in Appendix A.

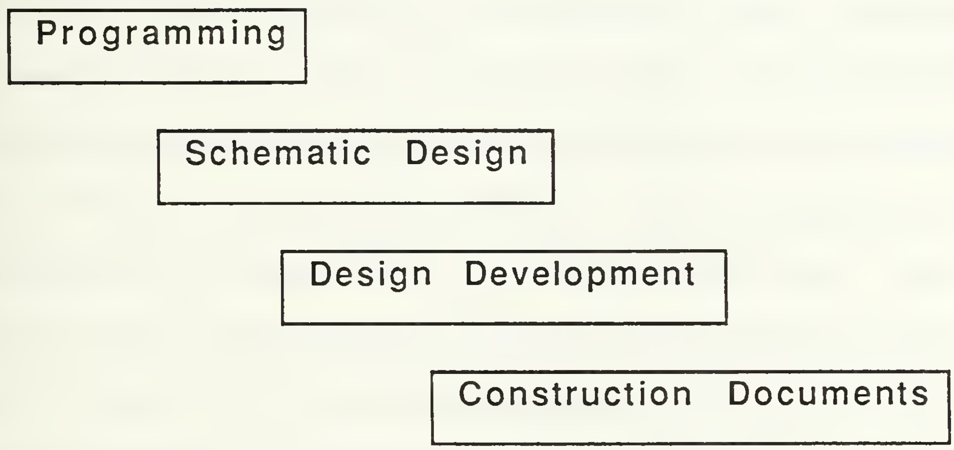

Figure 1.2 Building Design Phases

The design effort from one phase to another is structured and determined by the RELATION between information within each

description and between information external to the descriptions. Eastman[5] classifies those relations as logical, (between descriptions), and technological, socio-economic, and behavioral, (these are between information in the description and information within the design context). Building designs must satisfy all four classes of relations, with the appropriate priorities and trade-offs determining the extent to which any class of relations is fully optimized. For example, it is desirable for a building to be as inexpensive to construct as possible, however initial costs must be balanced against aesthetics and durability.

The different relations can be understood as the different design perspectives. For a building, there are many different design perspectives, each of which can affect the course and outcome of the final building design. Each perspective looks at the design for issues that it is concerned with. The user may look at the design to see how well the building plan will function to serve its intended purpose. A fire marshall will look at the design to ensure that the health and safety of building occupants is accounted for by adequate numbers and placements of fire exits and extinguishing systems. A contractor or construction manager will look at the design to see how easily it can be built.

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[5] Charles M. Eastman, "The Scope of Computer-Aided Building Design," in Spatial Synthesis in Computer-Aided Building Design, ed. Charles M. Eastman (New York: John Wiley and Sons, 1975).

There are many relations in each class of relations, and their number and relative importance changes from building to building. Eastman[6] relates the number of relations to the problem of computer aided design:

> "Within each class of relations there exist whole areas of knowledge, which certainly cannot be enumerated here. They are expected to be incorporated into designs for building and the effect has been to expand the scope of the design process. Building design firms have significantly increased in size and include a much greater diversity of personnel than previously. Any comprehensive approach to computer aided building design must also respond to this diversity of information."

Due to the different relations, and the different building systems required to be described, it is clear that there must be thousands of subtasks required to complete each phase of building design. Each subtask requires different knowledge and possibly different people for its performance. The descriptions that are required for each phase are subsequently the results of thousands of decisions and access to many different knowledge sources. System descriptions within and between each phase of design may change many times due to the interplay of the subtasks and the balancing of the different relations. It is not difficult to understand why so many people are required to manage and perform the sequential translation of a design from one phase to the next.

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[6] Ibid.

Building Systems and Their Descriptions

The complete and final "design" of a building which is used to guide construction is manifest in the building's construction documents. The construction documents include two basic types of descriptions, 1. the drawings, and 2. the typed specifications which describe the required quality of materials and construction. To accommodate the organization of the entities which perform design and construction (described later), the drawings and specifications are organized by the major functional systems of the building. For example the construction documents of the Operational Control Center at NAS Brunswick, Maine consisted of a total of 137 - 30"x40"- sheets of drawings which were categorized as either civil, architectural, structural, plumbing, HVAC, or electrical. The specifications document was 5" thick and included 16 building system divisions and 95 subdivisions.

The American Institute of Architects and the General Services Administration have developed a building system classification system called UNIFORMAT which is used for design cost control.[7] Levels 2 and 3 of this system describe the different systems of a building. These are shown in figure 1.3 below.

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[7] Brian Bowen, "B-5 Design and Construction Cost Management," in Architect's Handbook of Professional Practice, ed. American Institute of Architects, (AIA 1984), p.5.

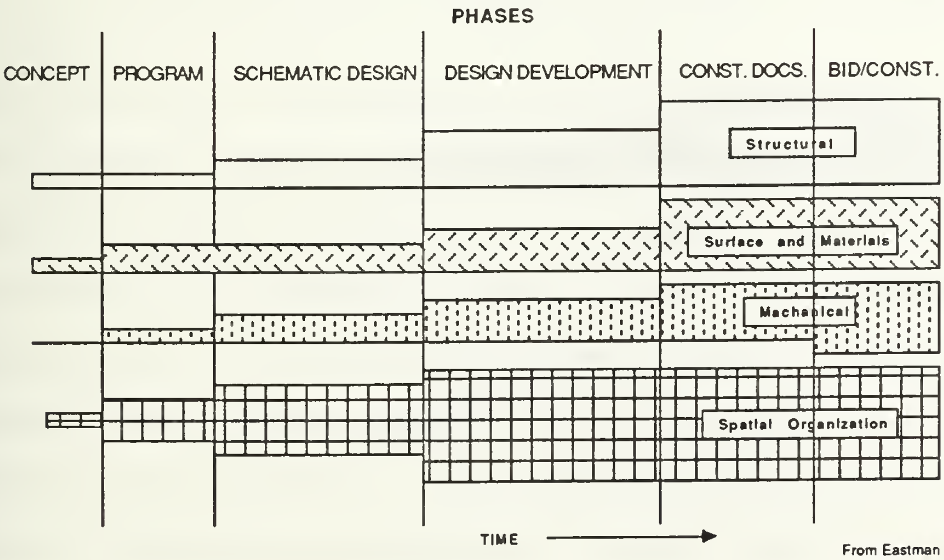
FIGURE 1.3 BUILDING SYSTEM CATEGORIES

1. FOUNDATIONS	1.1 Standard Foundations 1.2 Special Foundation Conditions
2. SUBSTRUCTURE	2.1 Slab on Grade 2.2 Basement Excavation 2.3 Basement Walls
3. SUPERSTRUCTURE	3.1 Floor Construction 3.2 Roof Construction 3.3 Stair Construction
4. EXTERIOR CLOSURE	4.1 Exterior Walls 4.2 Exterior Doors and Windows
5. ROOFING	
6. INTERIOR CONSTRUCTION	6.1 Partitions 6.2 Interior Finishes 6.3 Specialties
7. CONVEYING SYSTEMS	
8. MECHANICAL	8.1 Plumbing 8.2 HVAC 8.3 Fire Protection 8.4 Special Mechanical Systems
9. ELECTRICAL	9.1 Service and Distribution 9.2 Lighting and Power 9.3 Special Electrical Systems
10. EQUIPMENT	10.1 Furnishings (Built-In) 10.2 Special Construction (Machinery/Equip)
11. SITE WORK	11.1 Site Preparation 11.2 Site Improvements 11.3 Site Utilities 11.4 Off Site Work

Each of the building's systems is developed concurrently over the course of the design process. The individual systems are developed at first independently and are then integrated with the other systems one or more times during each phase of design.

> "The relative effort on each of the subsystems will vary over time, depending on the particulars of a specific project. The total effort may thus be decomposed as shown in figure 1.2 [My figure 1.4], where the width of band for each subsystem represents the amount of information available about it over time. If a band expands during any phase, this means that its information base is expanding. In other words, decisions are being made about that subsystem in this phase of design. Overall, information about each subsystem accumulates, but at various rates..... in general, then, methods of analysis and decision making are required for each subsystem during those phases when its information base expands."[8]

FIGURE 1.4 Description Information Growth



From Eastman

[8] Eastman, "Computer Aided Design", pp. 7,8

As the design phases progress, the system descriptions can be divided into subsystems. Thus the system descriptions are composed of two or more subsystems, and the subsystem descriptions are composed of component descriptions. Generically then, we have a hierarchy of descriptions which is graphically demonstrated in figure 1.5.

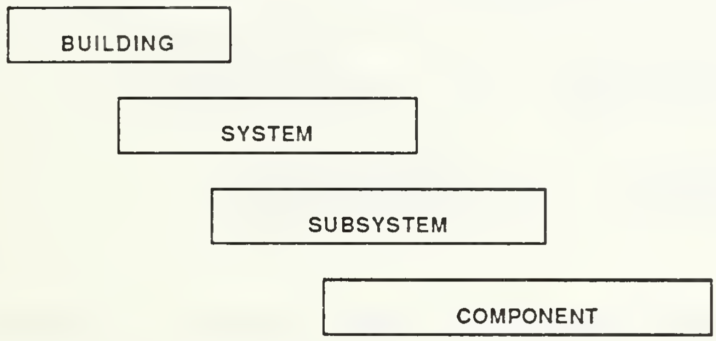


FIGURE 1.5 Building System Description Hierarchy

Thus we see that the phases of design are basically related to the different levels of the system description hierarchy. The programming phase is related to the general building description, the schematic design phase to the system descriptions, the design development phase to the subsystem descriptions, and the construction documents phase to the component descriptions. The description hierarchy and the American Institute of Architects' design phases are shown superimposed in figure 1.6.

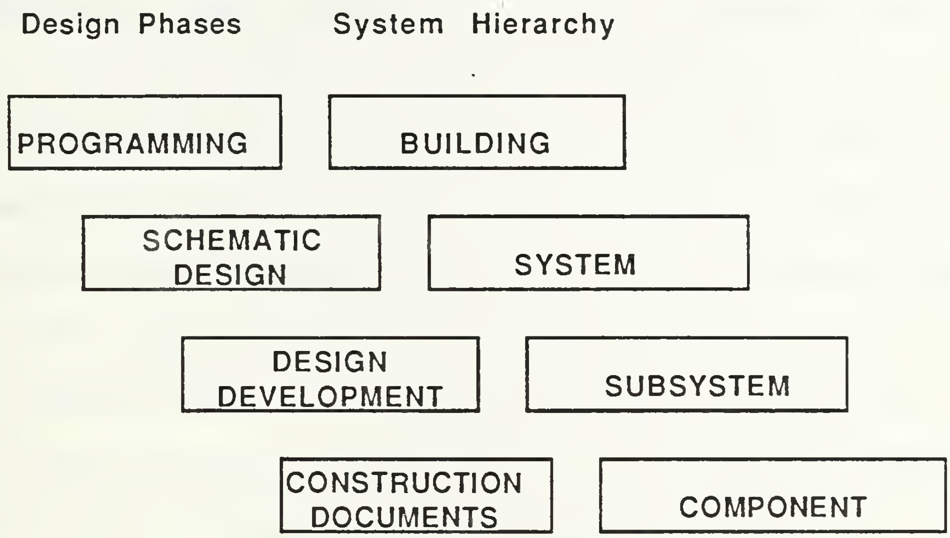


FIGURE 1.6 Design Phases and System Hierarchy

Apparent Complexity is an Actual Benefit

Imagining all of the decisions required for the complete design of one major building system gives us some sense of the number of the basic design cycles required for designing a total building. At each decision point, the analysis, synthesis, appraisal routine may be repeated a number of times as each design perspective is considered. The total decisions

must number in the tens of thousands, but because the design process is ordered, the individual decisions are not that difficult to make. Each successive decision is built upon the information in descriptions from previous decisions. This mapping of decisions one on top of another at once makes each decision easier yet the description more complex. Ironically, the more complex and detailed the design description is, the easier it is for designers to make subsequent decisions. Similarly, the more detailed a building design, (assuming correctness and clarity are consistent), the easier it is for the constructors to comprehend the designers' intent.

The Design Team

Once beyond the scope of a very small building, the complexities and requirements inherent in a building design cause its creation to be beyond the ability of any one person. Not only would the different types of knowledge be difficult for one person to master, but one person designing a whole building would take too long. The design team has become the standard organization for building design.

Design team members usually specialize by building system. A design team may consist of architects, interior designers, landscape architects, civil engineers, electrical engineers,

mechanical engineers, and other consultants as needed. The Control Center design team is shown in figure 1.7.[9]

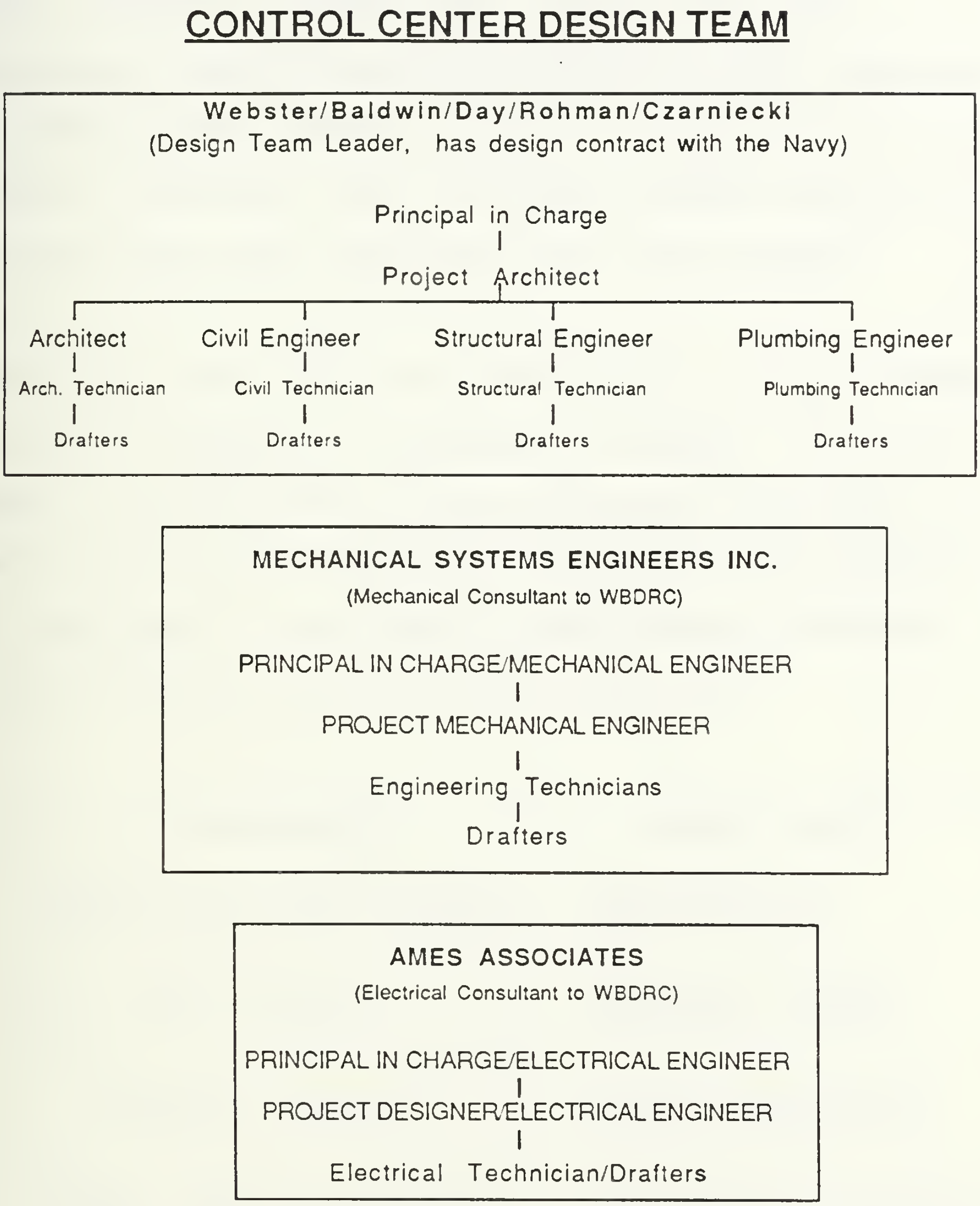


FIGURE 1.7 Control Center Design Team

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[9] The information about the design team came from Mike Czarniecki of Webster/Baldwin/Day/Rohman/Czarniecki, George Ames of Ames Associates, and Richard Whitney of Mechanical Systems Engineers. They each were project designers for the Control Center.

As can be seen from the figure, each major team member is actually a group of members. The size of the group is mandated mostly by the knowledge requirements, but, significantly, also by time requirements. Time requirements can be broken into two major issues: 1. we can't take forever to design a building, and 2. different people occupy the team member positions over the course of a major project.

Interestingly, the skill and importance of the team members in a group will change with the phase of design. It is not uncommon to find a design firm's principal doing most of the schematic design, an associate doing the design development, and a draftsperson preparing the construction documents. This phenomena is shown graphically in figure 1.8.

TEAM MEMBER	DESIGN PHASE
Owners with Firm Principal	Programming
Firm Principal	Schematic Design
Associate Designer	Design Development
Design Technicians/Drafters	Construction Documents

Figure 1.8 Team Members and the Design Phases

The Interaction of Players

Figure 1.9 below shows the complex input relationships matrix between members of the design team and the different systems descriptions of a building.

Designer \ Building System	Foundations	Substructure	Superstructure	Exterior Closure	Roofing	Interior Construction	Conveying Systems	Mechanical	Equipment	Electrical	Site Work
Architect	x	x	x	x	x	x	x	x	x	x	x
Civil Engineer	x	x									x
Structural Engineer	x	x	x	x	x	x	x	x	x	x	x
Plumbing Engineer		x			x	x		x			x
HVAC Engineer			x	x	x	x		x	x	x	
Electrical Engineer		x		x	x	x	x	x	x	x	x
Interior Designer				x		x	x	x	x	x	

FIGURE 1.9 Designers' Input to Building Systems

If the systems in figure 1.9 had been broken into subsystems, and the design group had been broken into individual members, it would be easy to see the magnitude of the complexity in the interrelationships of a building design team. But we find again, when well managed, the apparent complexity actually makes the design process simpler. If each team member has a specific task to do, knows how to do it, and does it well, then that specific task is easily performed. This is because each team member does not face the total complexity as shown in figure 1.9. Each design task requires limited input from other sources.

Other Designers

In traditional building design, design detail in some areas is left up to suppliers and/or fabricators, and is performed during the construction phase. These detailed, component specific designs are known as shop drawings. It is both the design professional's and contractor's responsibility to ensure that design intent and integrity have been maintained by the supplier or fabricator. Shop drawings effectively add the supplier and fabricator of certain subsystems, to the design team. The use of shop drawings therefore extends the design phase into the construction phase of a building construction project.

One essential, but not obvious member of the design team, is the owner of the building. Many design descriptions such as models and rendered perspectives are provided specifically to help the owner make design decisions. The owner may at times be the least trained but most powerful member of the design team. Depending on the owner's background, he may influence all or relatively few system designs.

In some cases, the Operational Control Center for example, there may be more than one owner that will have input into the design process. The Control Center was to be the home of five separate organizations. The five organizations were composed of an average of three branches, effectively making the owner a fifteen person entity. Interestingly, these fifteen people had to service and support each other in various ways such that each person had design input which was influenced by one or more requirements placed on him by another "owner".

Summary

We have shown that a building is an assemblage of components organized as systems, and the systems work together to provide an environment appropriate to the activity which the building serves. The design of the building is performed in phases.

Each phase of the design produces descriptions of the building to the extent that the next phase of design can begin. The design work is performed by many people, whose individual expertise corresponds to the building's systems and subsystems. Although many people and systems are involved and interrelationships are numerous, the individual design decisions are more easily made as the design process proceeds and more decisions are made. We will now turn our efforts toward desribing the second major aspect of the context of constructibility, the processes and players which comprise building construction.

Building Construction

For our purposes we will define the construction phase of a building project to begin at the time when constructors get involved. In a competitively bid, fixed price construction contract scenario, contractors usually do not get involved until the contract is "advertised" for bids. A good benchmark for the completion of construction activity is the expiration of the general warranty for construction. Although the contract may require that specific pieces of equipment be warranted for longer periods, (roofs also are usually required to have a longer warranty period), the general requirements of a contract require a warranty period of one year commencing at the date of substantial completion or beneficial occupancy. Figure 1.10 illustrates the elements of the construction phase of a project.

ELEMENTS OF THE CONSTRUCTION PHASE

Contract Advertisement	Estimating the work	Assembling a Bid	Bidding
General Contract Award	Scheduling the Work	Mobilization	Material Procurement
Subcontract Awards	Shop Drawing Submittals	Construction Operations and Coordination	Progress Payments
Testing/Inspection	Acceptance at Completion	Final Payment	Warranty Period Work

FIGURE 1.10 Elements of the Construction Phase

The Bid Phase

Once the plans and specifications are completed by the architects and engineers, a bid package is put together and the owner of the building puts out an invitation to bid. This invitation can be extended to a preselected group of building contractors, or it can be advertized on the open market.

Before the owner extends the invitation to anyone, he usually decides whether he wants to negotiate the construction contract or award it on the basis of the low competitive bid. Governmental bodies usually award their construction contracts on the basis of the low competitive bid. Private owners have traditionally used many different forms of award methods, from competitive open bidding, to handshake agreements with a contractor friend. For convenience, I would like to choose the U.S. Navy's usual method of construction contracting, competitive open bidding, as a basis of our study. In this form of bidding, any contractor is allowed to bid on the work as long as he or she can meet the bonding and insurance requirements, and other requirements of the contract. Bids are usually opened after a bid period of between thirty and sixty days, and the contract is awarded to the low bidder. The four case studies described later in this thesis were bid and awarded in this fashion.

The Bid Package

The owner assembles a bid package which consists of the drawings, specifications, bid forms, instructions to bidders, and General Conditions of the contract. Once everything in the bid package is checked by the appropriate parties, the owner advertises that he is accepting bids for the work. Advertizing is done in local newspapers, trade journals, and the Commerce Business Daily, which is a daily journal which lists U.S. Government procurement invitations, contract awards, subcontracting leads, sales of surplus property and foreign business opportunities. The advertisements list the location of the work, the approximate cost of the work, and give a breakdown of the work by system, so that specialty subcontractors can quickly determine if the solicitation contains work in their area of expertise.

In addition to being able to respond to the advertisements, contractors can apply to be put on a bidders list for certain types of contracts. When a solicitation includes work pertaining to a bidders list, the people on the list are automatically sent a pre-solicitation notice, which is a description of the work, without any further request. Contractors must make a formal request to the contracting officer in order to receive the full bid package. Contractors can also request a copy of a form that lists all contractors

that have received a copy of the bid package. General contractors can use this list to see what subcontractors are interested in giving sub bids, and subcontractors use the list in order to determine what general contractors might be interested in receiving a sub bid. Receipt of a bid package does not make a contractor responsible for having to submit a bid.

Both general contractors and specialty subcontractors receive copies of the total bid package. Once the different contractors receive the bid package, they determine which portion of the work that they as an entity would like to perform. Although the owner awards only one contract, there may be dozens of business entities that will be performing the total work. Thus as in designing the work, there is a hierarchical contracting arrangement for the construction of the design. An example of a possible contractual hierarchy is shown in figure 1.11.

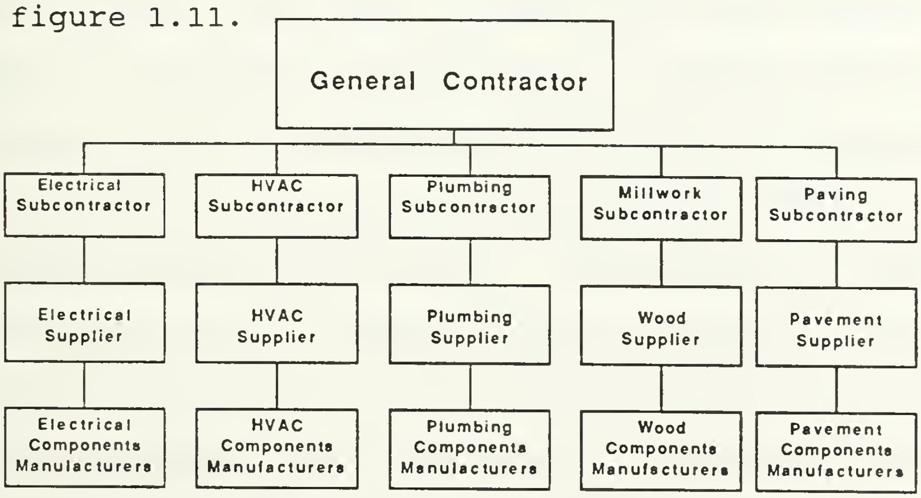

FIGURE 1.11 Construction Contract Hierarchy

It is interesting and important to note that the construction contracting hierarchy is similar to the design team hierarchy shown previously in figure 1.7. Subcontractors, like design firms, are usually organized to specialize in one system or subsystem of a building. Material vendors are also interested in contract solicitations, and are called upon by contractors to provide a price for the materials required to carry out the work. In general, material suppliers also specialize by building system or subsystem. Thus, a building's electrical system will be designed by an electrical engineer, and will be built by an electrical subcontractor with materials supplied by an electrical materials and equipment supply wholesaler.

Once the contractors receive the bid package, they begin to determine which portion of the work that they want to perform, and what contractual relationship they would like to have. Some contractors have the ability to perform the coordinating duties of a general contractor, (sometimes called prime contractor), in addition to performing a certain part of the building work. Other contractors prefer being subcontractors to a general contractor, and to be responsible for building only a certain portion of the work. Contractually, general contractors enter into a contract with the owner and are responsible to the owner for providing the complete facility. The general contractor then contracts with the subcontractors, who then are responsible only to the general contractor, for

providing the construction of a portion of the work.

Estimating the Work

After deciding which portion of the work they would like to perform and their preferred position in the contractual hierarchy, the contractors perform material and quantity take-offs from the drawings and specifications[10], and estimate the cost of their portion of the work. This is done by people specially trained in estimating, using company-specific historical records, rules of thumb, current equipment rental or ownership costs, and overhead rates. During the estimating period the contractor will also develop a preliminary plan for construction, and identify materials or equipment that require long lead times which may affect the construction plan. The contractor will also determine which methods or techniques he will use for construction, and estimate the costs of the equipment and tools required for the particular methods chosen.

In the course of estimating the work to be performed, contractors will usually come upon deficiencies in the bid documents that inhibit their ability to prepare an accurate

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[10] The drawings and specifications comprise the design which was prepared by the architects and engineers. They are the only documents used as a basis for a bid.

bid. Unclear quality specification, conflicts between the drawings and specifications, missing or unfinished system descriptions, are examples of such deficiencies.[11] When contractors come across such deficiencies they are required to contact the contracting officer to request a clarification. At times the contractors opt not to disclose the deficiencies and decide to base their bid on what they think is appropriate, and wait until the contract is awarded to request clarification. In this case the contractor would expect to be reimbursed any costs which the actual requirements entail beyond his estimate.

Contract Amendments

When contractors do notify the contracting officer of a deficiency during the bidding period, the owner and the designers examine the question and determine whether a clarification is needed. If a clarification or correction is needed, all bidders are notified thereof in the form of an amendment to the solicitation. Amendments are written documents which are sent to everyone who has taken out a bid package. The amendment clarifies, corrects, adds or subtracts work in the bid documents. In this way, no one contractor is

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[11] These and other design document deficiencies will be categorized in the constructibility section of this thesis.

privileged with obtaining information which his competitors might not have.

If an amendment modifies the work in a major way, or if the amendment is distributed late in the bidding period, the bid period is extended by an appropriate amount of time. This allows time for the contractors to incorporate the amendment into their bid estimate. Contractors must acknowledge receipt of all amendments in order to validate their bid on the bid opening date. A bid may be disqualified as non-responsive if all amendments are not acknowledged.

Assembling a Bid

Usually on the bid due date, or the day prior, general contractors accept sub bids from many subcontractors and assemble a bid for the total work. The sub bids are quoted, usually over the phone, in two parts, price and scope. The General contractors (Prime Contractors), assemble the sub bids ensuring that they cover 100% of the scope of the work for the lowest, best price.

The art of being a successful prime contractor manifests itself at this crucial point. Knowing when a sub bid is too low, or if the total scope of the work is covered, is critical

to the success of a project. For example, a contractor may receive four or five sub bids for electrical work which vary substantially. However the low bid may not be the best bid, or it may cover a smaller scope of work than the other bids. Some bids may cover a scope of work beyond the other bids, and even overlap with the scope of sub bids from other building system subcontractors. For instance, an electrical subcontractor may cover wiring and supplying the electric motors for an exhaust fan in his bid price. At the same time, the mechanical HVAC subcontractor may also be including the fan motors in his price. If the General Contractor chooses to combine the bids, then there is a duplicated cost which can make his bid less competitive. On the other hand, both the electrical and mechanical sub bids may exclude the cost of the motors, and the combined price may be too low. In this case the General contractor may win the contract but lose his shirt when he finds out that his price is not adequate to cover all of the costs.

Bid Submission and Contract Award

After the General contractors assemble the best bid package they submit a sealed lump sum bid for the total work as prescribed by the instructions to bidders, by the bid due date. At the time of the bid due date, no further bids are

accepted and the bids are opened publicly. A contract is subsequently awarded to the low bidder who has been responsive to all of the requirements of the solicitation, and is known to be a responsible contractor. Subcontractors who offer bids to many different prime contractors have a better chance of acquiring the work than if they only offer a bid to one prime. Subcontractors are also in a position to affect the competitiveness of the prime contractors due to the fact that the same subcontractor can give different prices to the different prime contractors. The material and equipment vendors are in the same position with the subcontractors, and may take advantage of their position to award good customers and discourage poor ones.

The Contractual Chain

After the owner awards the construction contract to the prime contractor, the prime contractor awards contracts to all of the subcontractors. At this time, the general contractor can choose to continue to shop for a better priced subcontract than he carried in his bid. Although this practice is an ethical gray area, it is widely done, and can quickly increase the profitability of the project to a general contractor. Once the subcontractors receive their contracts, they are able to write purchase orders for the material and equipment

required to perform the work. These purchase orders are essentially contracts with the material and equipment suppliers based on previously quoted prices.[12]

Sometimes a problem arises when a contract is not awarded within a reasonable time from the bid opening date. Material quotes and subcontract bids are normally good for sixty days. A prime contractor must be very careful to check the current prices from the subcontractors and his suppliers before he accepts a contract award which is offered beyond sixty days from the original bid date.

Post Award and Construction Phase

Once the prime contractor is awarded a contract to construct a building, he awards contracts to his subcontractors, usually in the order which he needs their services. The contractor also must purchase insurance before he can start work. When the contractor is ready to proceed, usually the first order of business is called mobilization.

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[12] Some items of equipment and material must be approved before a subcontractor should issue purchase orders to his supplier(s) for those items.

Mobilization

Mobilization covers such activities as bringing portable office space onto the site, including all necessary temporary utilities to support the offices. The offices are usually rented and are in the form of a house trailer. Trailers are also moved onto the site for tool and material storage. Porta-Johns and pay phones are also placed on the site for the benefit of the workers. If required by the construction contract, or for the contractor's security requirements, a fence is sometimes erected around the perimeter of the site. Building Access roads and clearing trees is also sometimes required before work on the actual building can occur. Mobilization would be completed when construction equipment, such as conveyors, air compressors, loaders, etc. were delivered to the site.

During mobilization the contractor's management personnel are usually preparing a construction schedule, which includes all of the construction tasks, but also all of the logistics tasks required to ensure that material and equipment were present when required. One very important aspect of the logistics plan is the "submittal" submission and approval process, which must precede the purchase of much of the material and equipment to be incorporated into the building.

Submittals

Submittals are required by the specifications for two reasons. First they give the contractor the opportunity to choose the make of certain material and equipment, and the freedom to optimize the fabrication and erection of systems and components through innovative design. Secondly, the submittal process gives the architect, engineer, and owner the chance to ensure that the contractors' selections meet the quality and performance requirements of the specifications.

There are generally three classes of submittals. The first class is shop drawings. Shop drawings are detailed design drawings usually prepared by a manufacturer, fabricator or supplier, i.e. by other than the design engineers or architects. Although prepared by others, shop drawings normally remain the responsibility of the project designers. The architects and engineers must be given the chance to review shop drawings for design integrity and either approve or reject them. It is the responsibility of the designer to make sure that the details of one system or its components are compatible with the details of other components within the same system, as well as with other systems and their components.

The other two classes of submittals are manufacturers'

specification sheets, and construction process descriptions which require approval by the owner before work can begin. This last class includes such things as a safety plan, a quality control plan, and the construction schedule itself. (Submittals are often referred to generically as shop drawings.)

Before a contractor purchases materials and equipment, or before he begins fabrication of any components, he must receive approval of those items which required submittals. If the contractor proceeds without approval, he proceeds at his own risk, and the owner can stop him from incorporating any unapproved items into the work, or direct their removal at no extra cost if they subsequently fail to be approved. The owner is also not obligated to make progress payments for any portion of work provided that has not received required submittal approval.

Submittals normally take two weeks to be reviewed and returned to the contractor as either approved or not approved. Thus if a piece of material or equipment is on the project's critical path, it is important for the contractor to get it approved as soon as possible so that the critical path is not affected. The shop drawing process thus extends the design phase directly into the construction phase. Design work is also performed as needed in the construction phase for

clarification, correction, or addition to the original design. This latter design is added to the construction contract in the form of change orders. Change order design integrity is also the responsibility of the designer.

Construction Activities

After mobilization and submittal approval, the contractor goes about the actual construction of the building according to the construction schedule. The general contractor coordinates the work of his own workers as well as the work of his subcontractors, ensuring that all work is performed in the proper sequence, at the proper time, at an acceptable cost, and of an acceptable quality. As work is performed it is inspected by the contractor and the owner for its conformance with the specifications. Usually the owner will designate the architect and his engineers as his agents for this inspection.

Progress Payments

At regular intervals the contractor will submit a request for progress payments to the owner via the architect. The architect takes measures to ensure that work which has been billed for has been adequately performed, and makes a

recommendation to the owner for payment under the terms of the contract. The general contractor in turn is billed by, and makes payments to, his subcontractors for their work. The owner normally retains approximately 10% of the payment due the contractor as a hedge against the possibility that the contractor will not complete the contract in its entirety. Upon final acceptance of the building, the owner will make final payment which will include all money retained from all prior payments.

Extent of Subcontracting in Building Construction

As stated previously, the general or prime contractor usually does not perform the majority of the building construction with his own employees. In the case of the Operational Control Center Project (One of the four case studies), the general contractor held subcontracts with at least twenty different subcontractors. Some of these subcontractors also had contracts with other subcontractors, thus creating another tier of contractors. Typically, a general contractor will provide the structural work and rough carpentry, while the other subcontractors perform the remainder of the work.[13] The

[13] This varies from company to company. Some general contractors may not perform any construction work at all, and provide only construction management and subcontractor coordination services. These companies are sometimes referred to as "brokers".

general contractor for the Operational Control Center had separate subcontracts for each of the following items of work: Access flooring and acoustical wall treatment, precast fascia panels, millwork, bituminous paving, chain link fencing, aluminum windows and curtain wall, carpet and floor covering, paint and wall covering, drapes and blinds, mechanical systems, electrical systems, site work, masonry, roofing and sheet metal, sprinkler system, gypsum partitions, halon fire extinguishing system, doors and door hardware, testing and balancing of the mechanical systems, and signs.

It is important to remember that the general contractor has not done any estimating of the work performed by his subcontractors, and is not familiar with the details of their plan of work. The general contractor's responsibility to coordinate the work of the subcontractors is performed primarily after the bid and award phases, and constitutes the bulk of his effort thereafter.

All coordination and communication between the owners, engineers, architects, and subcontractors is via the general contractor. The communication and coordination path is shown schematically in figure 1.12 below.

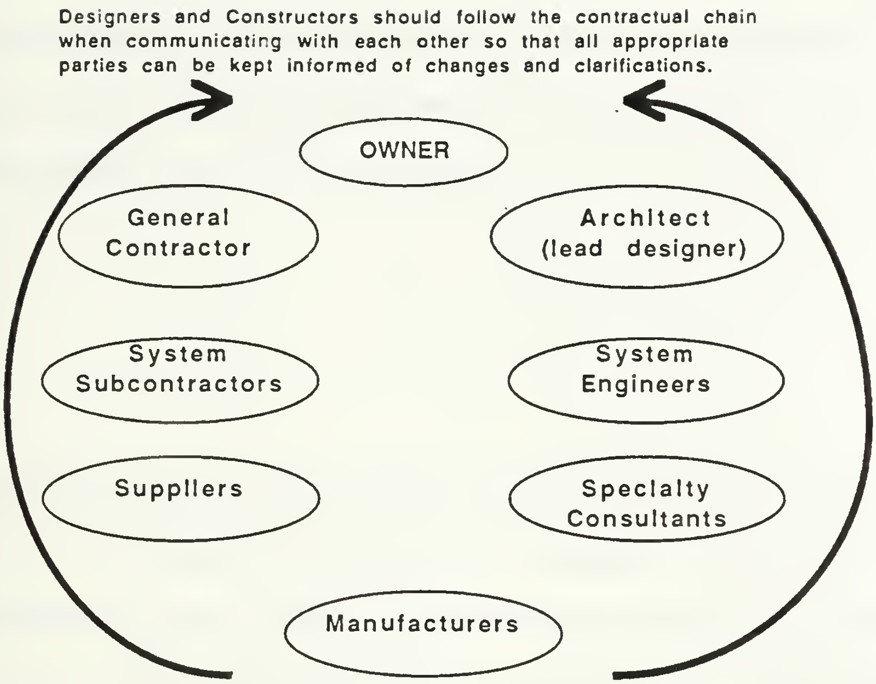

FIGURE 1.12 Construction Project Communication

The Construction Team

Figure 1.12 thus shows graphically the roster of the building construction team. The lineup positions seldom change, however the people within each organization can and do change. The personnel turnover in a project greatly affects the performance of the already complex and large network. The baseball analogy to the construction team concept would be teams from two different leagues (design league and construction league), trying to play each other with a strategy such that neither side will lose, while players in each position retire or are traded to other teams during the course of the game. The point being simply that the

construction process is not at all simple when looked at objectively from the dugouts, when it might look like just another ballgame from the bleachers.

Summary

In this section we have described the processes and players involved in a building's construction phase. We have shown that the drawings and specifications which comprise the building design are assembled in a bid package, and bids are solicited. Contractors interested in performing any work contained in the bid documents use the documents to estimate the cost of the work. General contractors assemble and total bids submitted by numerous subcontractors. Subcontractors' bids cover the cost of work which that subcontractor will perform, which is usually concentrated in a specific building system or subsystem. General contractors submit bids to the owner and a contract is awarded to the contractor who has submitted the lowest responsive and responsible bid.

After the owner awards a contract to a general contractor, the general awards subcontracts to the specialty subcontractors, and they in turn award contracts (in the form of purchase orders) to their material and equipment suppliers. Materials and equipment requiring approval, and detailed shop drawings

are submitted to the owner for approval. The designers review the submittals for the owner and ensure that design intent and contract requirements are not compromised. Meanwhile the contractors are mobilizing at the construction site, and work is planned and scheduled. Actual construction then proceeds according to the schedule and progress payments are made to the contractor by the owner as work is performed. Final payment is made upon successful completion of the work.

The construction team coordinates with the design team during construction to ensure completion of the actual building. There are many individuals and parties involved in the long process of construction. Specific individuals on the construction team may change during the process causing losses to the corporate knowledge base, however since the design documents give direction to the process, ideally new players can be brought in mid-phase and the construction can proceed smoothly.

When the design documents are lacking in practicability, correctness or clarity, the construction process will be affected. During the bid phase problems or opportunities inherent in the design documents may be noticed and are covered by amendments to the solicitation. If problems or opportunities are discovered after award of the contract, change orders are issued to modify the documents as required.

These problems and opportunities define the constructibility of a building design. We will now begin our focus on the concept of constructibility.

Constructibility: Definitions and General Discussion

Now that we have a basic understanding of design and construction, we can begin to investigate the concept of constructibility. We will start by analyzing some definitions of constructibility, and then look at some reasons why it is important to optimize constructibility.

Definitions

The Constructability[14] Committee of the Construction Industry Institute defines constructibility as follows:

> "Constructability is defined as the optimum integration of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall project objectives."[15]

This is a broad, general definition but it does indicate outright that the knowledge involved in constructibility is

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[14] The Construction Industry Institute prefers the spelling constructability. I have used that spelling in all quotes and references to the work done by people who use that spelling.

[15] Robert F. Jortberg, "CII Constructability Task Force Report," Transcripts of Presentations CII First Annual Meeting, Keystone, Colo., Aug., 6-8, 1985, pp. 147-175.

construction knowledge.

One of the Navy's engineering field divisions, has defined constructibility as:

> "...the practicability and correctness of a project design, including the inherent capability of the contract documents to be understood, bid, administered and enforced."[16]

The Navy's definition is more precise in that it establishes constructibility as an ATTRIBUTE of a project's DESIGN. It further goes on to suggest that there are three major issues of constructibility which we will call: <u>Practicability</u>, <u>Correctness</u>, and <u>Clarity</u>.

Constructibility is an Attribute of a Building's Design

Constructibility, as an attribute of the design, is distinct from other design attributes, but shares parts of the other design attributes. Some of the other attributes that a design has are shown in figure 2.1.

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[16] Constructibility Review Guidance, Western Division, Naval Facilities Engineering Command, December, 1983.

SOME BUILDING DESIGN
ATTRIBUTES

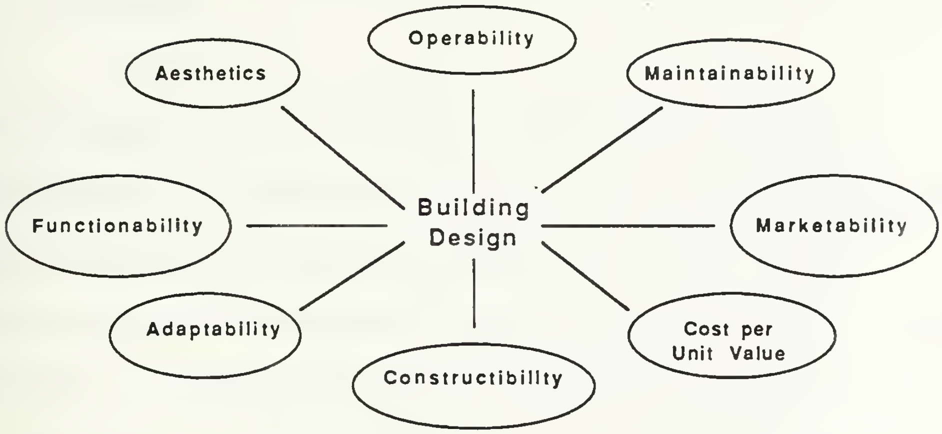

FIGURE 2.1 Attributes of a Building Design

Basically, the concept of constructibility refers to how constructable the design is. A very constructable design will usually make the construction phase go smoothly and without major cost or schedule overruns. A less constructable design could cause major problems for all parties during the construction phase. A recent ENR article[17] describes a roadway work contract in New York City which benefitted from a design that was completely re-engineered for constructibility at the start of construction. The article contrasted that successful project with another just a few miles away which was shut down after the joint venture contractor and owner failed to overcome design, construction, and administrative problems. The lack of constructibility in that design is

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[17] "Aging highway gets load off its feet, Constructibility review held costs in check for New York City Rehab," ENR, May 5, 1988, Vol 220, No. 18, pp. 24-26.

manifested in a pending claim by the contractor for $33 Million in damages.

If we use Eastman's terminology as mentioned earlier, constructibility is one of the relations which should guide the design process and design decisions. It is the perspective of the constructor and the construction contract administrator. Constructibility encompasses issues such as the appropriateness of the design to local construction techniques, the relative simplicity of the design, the time alloted for construction, the completeness of the design, physical interferences inherent in the design, conflicts between the plans and specifications, and administrative concerns of how bid-able and contractible the design is, i.e. how organized the drawings and specifications are and how clearly spelled out the contract requirements are.[18]

Constructibility Improvement

When we talk about improving the constructibility of a building design, we are in essence discussing how we can minimize and optimize the resources required for construction of the building. These resources are time, labor, material,

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[18] These and other categories of constructibility issues will be examined in detail in the next chapter.

equipment, and management. Minimizing or optimizing any of these resources will result in minimizing or optimizing the costs of construction.

In order to improve the constructibility of a design, knowledge of construction is required. Construction knowledge can be categorized into the areas shown on figure 2.2. Knowledge of typical consructibility problems and opportunities is also required in order to understand how and where construction knowledge must be applied.

We Maximize Constructibility
in order to
Minimize and Optimize the
Construction Resources
Required to Build a Building

Construction Resources

Time
Labor
Material
Equipment
Management

This requires knowledge of

Construction Sequences
Construction Trades
Construction Industry Organization
Construction Contracts and Law
Construction tools, techniques, and equipment
Construction testing and Inspection
and
New Construction Technologies

FIGURE 2.2 Types of Construction Knowledge

Why Worry About Constructibility?

Often when a project design is being rushed through a design office you will hear the phrase, "...they'll take care of it in the field". Yes, they will take care of it in the field because ultimately, all problems or deficiencies must be solved and resolved. The problem with taking care of it in the field is that it costs more in time and money. Figure 2.3 shows the savings versus time curve.[19] It illustrates clearly that the earlier a problem or opportunity is recognized and resolved, the more lucrative will be the discovery.

There also can be significant value lost when constructibility opportunities are missed. Often, a lack of interest or knowledge, or lack of time to plan or innovate, on the part of the designer is what perpetuates familiar construction technology and prevents designers from taking advantage of opportunities to improve a design's constructibility. The bottom line, according to the Business Roundtable's estimate, is a constructibility payoff of 20 to 1.[20]

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[19] Brian Bowen, "B-5 Design and Construction Cost Management," in Architect's Handbook of Professional Practice, ed. American Institute of Architects (AIA 1984), p. 3.

[20] Clyde B. Tatum, "Improving Constructibility During Conceptual Planning" Journal of Construction Engineering and Management 113 (June 1987): p. 205.

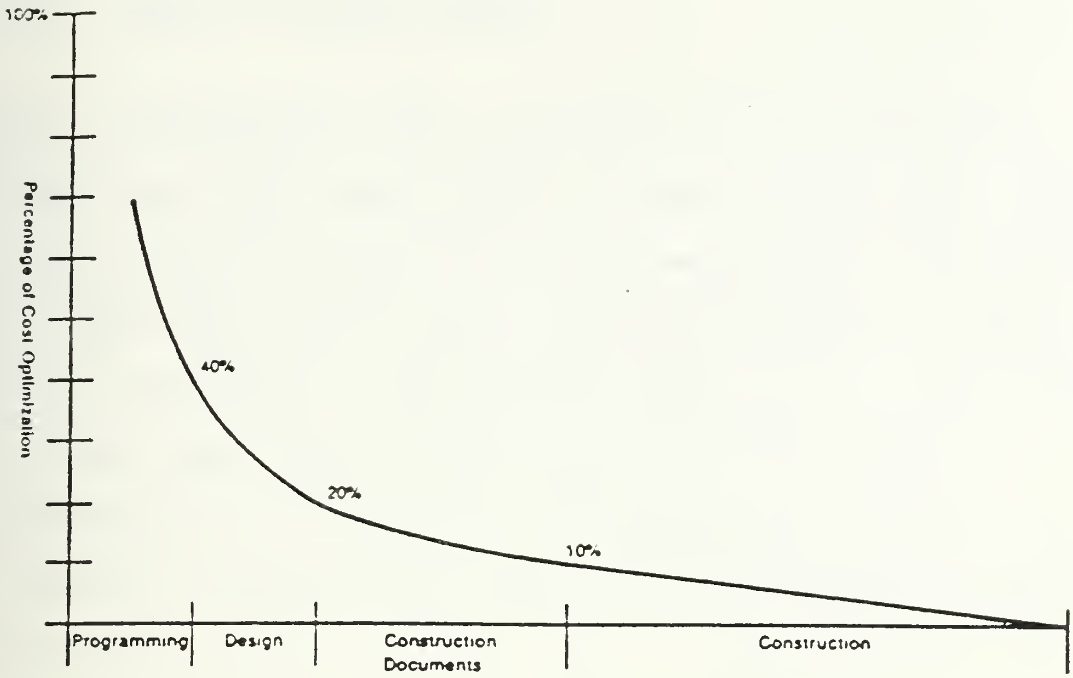

FIGURE 2.3 Savings versus Time Curve

The Costs of Constructibility as Measured by Change Orders

In construction contracting terms, a clear measure of the constructibility of a design is the number of changes, clarifications, and corrections required during the construction phase of the building project. These changes cost the project both time and money, even when they might deduct costs from the contract amount. In general there are three types: field changes - changes or clarifications to the design which do not involve time or money; change orders - changes to the design which involve time and/or money; and claims - change orders which are in dispute between the contracting parties.

Monetary Costs of Change Orders

Diekmann and Nelson[21] report in a study of 22 construction projects which had a total of 427 claims, (in this use a claim is actually just a change order, not necessarily a dispute as well), that fully 46% of additive claims were due to design errors. Each additive award averaged $19,900.00. The study also showed that Value Engineering, i.e. optimizing the constructibility of the design, accounted for 32% of all of the deductive claims, each of which was settled for an average of $8,000.00.

Naval Facilities Engineering Command, (NAVFAC), had a construction work effort of $2,862,800,000.00 in fiscal year 1987. The change order rate for these contracts was 5.1 %, amounting to a cost of $146.3 Million.[22] The civilian sector also has a change order rate which averages about 5% of total construction costs.[23]

The cost of the change orders is a significant amount of

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21 James E. Diekmann and Mark C. Nelson, "Construction Claims: Frequency and Severity," Journal of Construction Engineering and Management 111 (March 1985): p. 76.

22 Robert Smith, Naval Facilities Engineering Command, interview of 19 July, 1988. Figures are from the end of FY 1987 Goal Progress Reporting System Report.

23 Interview with Mr. Bob Weatherill, AIA, partner in the firm of Wadsworth, Boston, Mercer and Weatherill, Portland, Maine, 7 May 1988.

money. However, we cannot claim that the full costs of change orders represents the costs of constructibility problems. In most cases a portion of the cost would obviously have been borne by the owner if the design had been sufficient enough to prevent the change. However, for a number of reasons, there is usually a net avoidable cost associated with most claims. This cost can be considered a penalty cost,[24] and is the cost which we hope to diminish as we increase a design's constructibility. In general, it is probably fair to say that the average construction contract will have change orders amounting to 5% of the total cost of construction. Approximately 20% of the cost of change orders is avoidable cost, therefore, it seems that at least 1% of construction costs are avoidable.[25,26]

The Costs of Missed Opportunities

What is not clear from the change order numbers is what cost savings are not realized because constructibility

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[24] For a complete discussion of Penalty Costs see: James W. Cowell, "The Effects of Inadequate Component Inspection on Facility Repair Projects" (Master's Thesis, M.I.T., June 1988), pp. 74-95.

[25] Interview with Joseph Gallant, Construction Project Manager for the Resident Officer in Charge of Construction, Naval Air Station, Brunswick, Maine, 7 May 1988.

[26] Interview with Bob Weatherill, 7 May 1988.

opportunities are missed. The value engineering clause in construction contracts is good but it induces very few contractors to look for and submit proposals for cost savings. Most contractors want to avoid the paperwork and red tape that such a proposal requires. Also, constructors tend to want to be constructors, not designers. The failure to design for the optimal use of construction resources in itself incurs an avoidable construction cost.

Change Order Effects on Project Duration

The direct monetary cost of change orders is but half of the story, however. There is also the effect on the schedule which the changes can cause. The Diekmann and Nelson report cited above indicates that 25% of the additive claims had time extensions attached averaging 20 days each. The administrative overhead to extend a contract a day can run into thousands of dollars for owner and contractor alike. The cost of money borrowed on a construction loan is quite significant on any substantial project. One million dollars, borrowed at a rate of 15%, costs the borrower 15/12 or approximately 1.25% per month, which is $12,500.00 per month, or $416.00 per day.

Constructibility Affects Competitiveness

From a broader point of view, Tatum[27] points out that attention to constructibility from the beginning of the design process will ultimately serve to increase the productivity and hence the worldwide competitiveness of the U.S. construction Industry. This is not just the view of the academics. A class at MIT taught by Jack Kavanagh, president of Badger America Inc., an international contractor in the oil industry, indicated a highly organized constructibility feedback loop to the design arm of the company, Badger, Inc.. The existence of the Construction Industry Institute's Constructibility Task Force, (at the University of Texas, funded and attended by large construction companies), gives further credence to the importance of the issue.

Constructibility in Other Industries

Constructibility is not just a concern of the building construction industry, either. In 1972, Bath Iron Works Corporation instituted a Producibility Assurance Program for the PF 109 Class Patrol Frigate. The program was based on the concept of designing the ship to fit the shipyard, that is, design a product which is suited to the production process as

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[27] Tatum, "Improving Constructibility," p. 204.

well as to its ultimate use. An interview with Mr. Dan Thompson, former head of Bath Iron Work's Design Division, and author of the Producibility Assurance Manual, made us both conclude that the Producibility concept was identical to the concept of constructibility in the construction industry. Just one item in the Producibility Manual, stud mounting minor brackets instead of hand welding, produced a cost savings of $13,000.00 per ship back in 1973. The initial issue of the Producibility Assurance Manual implied a cost savings of $300,000.00 per ship.[28]

Bath Iron Work's Producibility Manual became a widely used design tool for shipbuilding designers throughout the industry. It is a method of transferring construction knowledge to the designers in order to optimize the design's constructibility. It produces both cost and time savings in ship construction.

The Problem

The problem that needs to be solved is that designers don't have the constructibility knowledge readily available to

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[28] Producibility Assurance Manual for the Patrol Frigate PF 109 Class, Bath Iron Works Corp., Bath, Maine, Mod 7, dated April 1, 1975.

recognize mistakes and opportunities, i.e. to optimize the constructibility of the design. Building designers are in need of a tool to help them recognize the opportunities and avoid the mistakes.

A tool, similar in concept to the producibility assurance manual in the shipbuilding industry, could be developed for the building construction industry to produce the same results. After a further investigation into the issues of constructibility in the next chapter, we will look at some ideas about the configuration of such a tool.

Chapter Summary

We began this thesis by discussing the context of constructibility, i.e. building design and building construction. We showed that building design has traditionally been performed in a certain process by a team of designers, each with an expertise in one or more systems or subsystems of a building. The whole design effort was shown to be needed solely for the end purpose of providing descriptions of the desired building to constructors who would build the building according to the design. Building construction was shown to have a certain process.

Construction was also identified as a team effort, this one composed of contractors, subcontractors, and suppliers, each with a special expertise in one or more of a building's systems or subsystems.

After discussing the context of constructibility, we looked briefly in this chapter at what we mean by constructibility. We determined that constructibility was an attribute of a building design, and that it was the perspective of the people who construct the building and administer the contract for construction. It can be decomposed into the three major issues of the practicability, correctness, and clarity of the design. We also stated that a design usually has both constructibility problems and opportunities, and that the knowledge to recognize these is construction and constructibility knowledge.

Improving constructibility has the effect of minimizing and optimizing the resources needed for building construction. We showed that optimizing constructibility was a concern of many in the industry, and that it resulted in savings of both time and money. Construction projects with major constructibility problems were subject to lengthy delays and large cost overruns.

Hopefully we now have a good understanding of the basic

meaning and context of constructibility. In the next chapter we will look at the issues of constructibility in more detail in order to gain a better understanding of the concept.

CHAPTER THREE - THE ISSUES OF CONSTRUCTIBILITY

Introduction

The Navy's definition of constructibility discussed earlier implies that there are three major issues to a design's constructibility: Practicability, Correctness, and Clarity. Under each of these categories there can be constructibility problems and/or constructibility opportunities, i.e. something that is not practicable, correct, or clear, or, something that can be more practicable, more correct, or clearer. We will begin this chapter with a discussion of these three major issues of constructibility in order to gain a full understanding of their meaning. I will present examples of each based on actual situations encountered on four building case studies.[29] The remainder of the chapter will discuss the specific categories in each issue of constructibility which need to be addressed in order for the constructibility of a building design to be optimal.

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[29] The information from the four case studies was collected through interviews with the project managers and from the construction contract files. The contracts and project managers are: Contract N62472-84-C-0355, Auto Hobby Shop, managed by LTjg Melody Spradlin; Contract N62472-84-C-0282, Patrol Aircraft Maintenance Training Building, managed by Joseph Gallant; Contract N62472-87-C-2530, New Telephone Exchange Building, managed by Thomas Sturgeon; and Contract N62472-85-C-0099, Operational Control Ceneter, which was managed by the author.

The Case Studies

The four case studies are all buildings substantially completed in 1987 or 1988. All four were built at the Naval Air Station in Brunswick, Maine, under competitively bid, lump sum construction contracts. Each building was new construction, and was basically a single story office building designed for a specific function. Brief descriptions of the buildings are given below.

The ASWOC

The ASWOC is the Antisubmarine Operational Control Center. It is a one story, 54,000 square foot building that houses the administration, communication, security, training, and operations functions of the Navy's submarine hunting P3 aircraft squadrons of Patrol Wing 5. The ASWOC replaced an existing group of 1950's vintage buildings, which were demolished under the same contract. The building was designed by Webster/Baldwin/Day/Rohman/Czarniecki of Bangor, Maine, and constructed by Reed & Reed of Woolwich, Maine. The construction contract was originally awarded at a cost of \$7,023,195.00, and as of modification number 58, the cost stands at \$7,731,460.59. Construction began in the Summer of 1985 and the building was substantially complete in the Fall

of 1987.

The PAMT

The PAMT is the Patrol Aircraft Maintenance Training Building. It is a one story, 32,000 square foot facility that supports the education and training of the personnel who perform maintenance and repairs on the Navy's submarine hunting P3 aircraft which are stationed at the Naval Air Station in Brunswick, Maine. The PAMT replaced two existing 1950's vintage buildings, which were not originally designed for maintenance training. The PAMT was designed by Webster/Baldwin/Day/Rohman/Czarniecki of Bangor, Maine, and constructed by Reed & Reed of Woolwich, Maine. The construction contract was originally awarded at a cost of $2,955,000.00, and as of modification number six, the cost stands at $3,029,997.00. 103 days were added to the contract due to the change orders. Construction began in the fall of 1986 and the building was substantially complete in the early spring of 1988.

The Auto Hobby Shop

The Auto Hobby Shop is a 12,000 square foot facility operated by the Morale, Welfare, and Recreation Department at the Naval Air Station in Brunswick, Maine. The building consists of twelve auto repair bays, a woodworking shop, recreational gear issue and storage rooms, offices, and associated support spaces. The Auto Hobby Shop replaced a "Butler Hut" type building built in the early 1950's, and is used by military personnel during off duty hours. The new building was designed by Webster/Baldwin/Day/Rohman/Czarniecki of Bangor, Maine, and constructed by D.L. Poulin Construction of Brunswick, Maine. The construction contract was originally awarded at a cost of $1,167,000.00, and as of modification number 16, the cost stands at $1,198,172.00. Eighty-five days were added to the contract due to change orders. Construction began in the Summer of 1986 and the building was substantially complete in the spring of 1988.

The Telephone Exchange Building

The Telephone Exchange Building is an 1,156 square foot concrete building comprised of an office space and a space for the telephone switching equipment that will serve the Naval Air Station at Brunswick, Maine. The building was designed by

Harriman Associates of Auburn, Maine, and constructed by H. E. Callahan Construction of Auburn, Maine. The construction contract was originally awarded at a cost of $162,000.00, and as of modification number 7, the cost stands at $169,378.00. Construction began during the summer of 1987 and the building was substantially complete by the end of the year.

The Major Issues

As previously claimed, there are three major issues of a building design's constructibility, its Practicability, Correctness, and Clarity. We will now discuss these issues and present clarifying examples from the case study projects. We will then further decompose the issues into constructibility categories.

Practicability

Practicability is basically a measure of how compatible the building design is with the project site, site conditions, and available construction materials and methods. Practicability applies to the placement of the building on the site, as well as to the selection and detailing of building systems, subsystems and components. Practicability is the issue of

constructibility that is in constant tension with the aesthetic attribute of a building's design. Often, practicability is subordinated to architectural effects desired by the designer.

Practicability also refers to the appropriateness of the building systems and their construction details. Often, construction details as designed are acceptable but not optimal when construction requirements are considered. There may be a quicker or more economical way to build something than as designed, while still achieving the desired architectural effect and maintaining the same structural integrity. There also may be ways to build something, that while just as costly as the designed configuration, result in a higher value due to an increase in the reliability or maintainability of the finished product. Practicability is the overriding justification of most value engineering type change orders to a construction contract. The use of appropriate new technologies is a major consideration under the practicability issue. New materials technology can quickly make tried and true designs impractical, or higher quality finishes more affordable.[30] Efficiencies of new construction equipment or techniques can be increased by the

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[30] As an example see the article by Barry Donaldson, "Stone: New technology and design," Architectural Record, July 1987, pp. 136 - 145.

designer, through design, if he knows they will be used.[31]

An Example of a Practicability Problem

An example of a practicability problem can be found in the design of the walls of the PAMT.[32] The PAMT building was designed to have exterior walls composed of full height precast concrete panels. Precast walls are not a problem in most areas, but it turns out that they are uncommon in Maine. At the time of bidding on the building, there were only two companies in Maine that had the capabilities to precast the wall panels. As it turned out, the precast subcontractor chosen by the prime contractor, was unable to meet the construction time schedule due to an overload of work. The prime contractor was forced to send his own employees to the

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[31] A lecture given on May 3, 1988 at M.I.T. by Frank Bassias, Head of the Boston Construction Managers employed by Turner Construction Company, made it clear that the existence and placement of the atrium in S.O.M.'s design of 75 State Street, Boston, Massachusetts, facilitated the use of the "Up-Down" construction technique and the Italian made equipment chosen by Turner as most appropriate for the technique. See also: Herb Lass and Susan Browne, "Pioneering earthy solutions," ENR, January 14, 1988.

[32] The following examples are provided solely to illustrate concepts and are not intended to imply failure or place blame on any person or entity. Situations described below are the rule, not the exception. Anyone who has been active in design or construction knows that just the completion of a building is a commendable achievement in itself. All opinions and judgments expressed in the examples are solely the author's and may not be correct.

precast plant in order to prevent major delays. Additionally, the prime contractor had to re-schedule the entire job and provide some temporary enclosure of the building so that interior construction could commence before the exterior walls were erected.

The exterior walls caused the contractor quite a headache and probably came at a cost premium to the Navy. A wall system of more common construction might have been more readily available, more reliably scheduled, and less expensive due to more competitive bidding. Interestingly, the details at the precast panel supports[33], and at the head and foot of the wall[34] were redesigned during the construction phase because of needed corrections possibly caused by an inexperience of the designers with this type of wall system.

Correctness

The correctness of a design is probably the most apparent aspect of its constructibility during construction. By correctness we are referring to the errors and omissions in the drawings and the specifications. Errors in dimensioning, interferences between systems, unbuildable or inoperable

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[33] Modification #3 to the PAMT Construction Contract

[34] Modification #4 to the PAMT Construction Contract

configurations, incorrect use of materials, missing details, and omitted systems or components required to make the building complete and usable, all come under the aspect of correctness. One of the major items that comes under correctness is unforeseen or hidden existing conditions. Although such conditions are generally not blamed on the designer, they are nonetheless a deficiency in the descriptive capacity of the design.[35]

Correctness issues are readily apparent in almost every change order under a construction contract. They are also the basis of all liability litigation experienced by designers. Millions of dollars and thousands of workdays are expended because of errors and omissions in building designs. Insurance companies and law firms thrive on the imperfection of the human design machine. It is very difficult, while involved in the problems encountered during construction, to step back and see how much of the design the designers got right! If a 5% change order rate implies 95% perfection, designers have a great record. Ted Williams never batted 950, yet isn't he a hero?

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[35] See the 1988 MIT Masters Degree thesis "The effects of Inadequate Component Inspection on Facility Repair Projects" by Jim Cowell for a review of the construction costs of unforeseen conditions and a cost/benefit analysis of the latest methods of determining accurate existing conditions before and during design.

Regardless of the amount of the design that is correct, we are challenged by the amount that is not correct. Building construction is not a game, it is big business and affects the lives, health, and welfare of virtually everyone. The following are examples of how the correctness of a design affects its constructibility.

An Example of a Correctness Problem

For an example of a correctness problem we will look at the ASWOC project. The ASWOC building had sheet rock ceilings in the computer rooms. The HVAC system ductwork with associated louvers and valves was located in the plenum above the ceiling. Their were no access panels specified or located in the design through which the HVAC system could be maintained, tested or balanced, after construction of the ceiling. A change order was required to add the access panels to the construction contract. The mechanical design engineer expended much effort locating and sizing the access panels. Additionally, the contractor was unable to complete work on the ceilings according to his schedule. The change order[36] increased the contract cost by $7,034.00, and extended the time by 15 days.

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[36] Modification #23 to the ASWOC Construction Contract

Clarity

The issue of clarity deals with the effectiveness of the descriptive capacity of the plans and specifications. The construction documents exist solely to guide the constructor in estimating, bidding, and constructing the building. This "reason to be" requires the documents to completely describe the building and all factors that might affect its construction, without any ambiguities. Clarity therefore is the relative effectiveness of the owner and designer in communicating their requirements to the constructor.

Since the language of building constructors is specialized, the designer must be able to communicate in that language. Optimally, the designer, owner, and constructor will speak a common language, with the same grammar, syntax, and definition. The constructibility of a design will suffer or benefit respectively based on the completeness, directness, and consistency of the information in the construction documents.

An Example of a Clarity Problem

One of the auto work bays at the Auto Hobby shop was planned

to hold a paint spray booth, which is a self contained, pre-engineered compartment designed for painting cars and trucks. Paint spray booths have specialized HVAC and fire protection systems, and are typically built in a factory and shipped to the construction site and installed as a unit into the building. The construction drawings for the Auto Hobby Shop showed where the paint spray booth was to be installed, and indicated some electrical and mechanical hook-up requirements. However, the contract specifications did not include any mention of the quality or performance requirements for a paint spray booth.

After award of the construction contract, the contractor asked the Navy what kind of paint spray booth they were going to install and when they would install it. The Navy responded by saying that the contractor was responsible for providing the paint spray booth. The contractor then claimed that the booth was not included in the contract, arguing that although its location was shown, there was no clear indication that the Navy had wanted the contractor to provide it. There was nothing in the specifications which mentioned the booth or its quality or performance requirements. Because of this, the contractor had reasonably assumed the booth would be furnished by the Navy, as were other pieces of equipment.

The result of the clarity problem in this case resulted in a

change order[37] to the construction contract by which the Navy paid $9,675.00 extra for the purchase of the paint spray booth. The contractor agreed to install the booth at no extra cost. Five days were added to the contract in conjunction with the change order.

Constructibility Categories

Hierarchically, constructibility is primarily composed of the three major issues of Practicability, Correctness, and Clarity as described above. These major issues can be further decomposed into **constructibility categories** which will help us further define what we mean by a design's constructibility. The categories encompass the specific and distinct generic problems and opportunities that can exist in a building design and affect its constructibility. Figure 3.1 is a listing of the constructibility categories under their major issue heading.

We feel that all constructibility problems and opportunities in a design can fit into one of the categories. The categories represent the specific constructibility issues which automated building design tools must be able to address

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[37] Modification #3 to the Auto Hobby Shop Construction Contract

to be of pratical and beneficial use. The categories are also presented as an organizational tool for use in the collection and study of constructibility knowledge. We will now discuss each category in some detail, giving actual examples from the case study buildings where an example will assist in explanation.

<u>CONSTRUCTIBILITY CATEGORIES</u>

PRACTICABILITY

Simplify Design
Standardization
Module Engineering/Preassembly Scoping
Accessibility
Adverse Weather
Specifications/Appropriate Quality
Local Construction
Adequate Time
Advanced and New Technologies

CORRECTNESS

Missing Requirements
New Requirements
Inoperable/Unfeasible Design
Interference
Unforeseeable Conditions
Unnoticed Existing Conditions
Incorrect Use/Application of Materials
Incorrect Dimensions
Code and Regulation Violations

CLARITY

Conflicting Plans and Specifications
Missing Specifications
Unclear Specifications
Drawing/Specification Location in Documents
Unclear Drawings

FIGURE 3.1 Constructibility Categories Under Major Issues

Practicability Categories

Simplify Design[38]

Simplifying the design for ease of construction is the basis of this category. The opportunity to do this is of course dependent upon how the simplification affects the operability, maintainability, and aesthetic attributes of the design. O'Connor et al give the following techniques to simplify a design for constructibility:

1. Use a minimum number of components, elements, or parts for assembly.

2. Use readily available materials in common sizes and configurations.

3. Use simple, easy to execute connections with minimum requirements for highly skilled labor and special environmental controls.

4. Design so that dimensional adjustments can be made in the field.

5. Design to minimize construction task interdependencies.

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[38] The categories of Simplify Design, Standardization, Module Engineering/Preassembly Scoping, Accessibility, Adverse Weather, and Specifications/Appropriate Quality are taken directly from research by James T. O'Connor et al that presents them as constructability concepts for engineering and procurement. For a complete discussion of these concepts, see: James T. O'Connor, Stephen E. Rusch, and Martin J. Schulz, "Constructability Concepts for Engineering and Procurement," Journal of Construction Engineering and Management Volume 113, Number 2, (June 1987): 235 - 248.

6. Consider handling, inspection, and testing requirements.

Simplifying the design does not refer to minimizing the drawings or specifications. The knowledge required to simplify a design is knowledge of material, tool, worker and equipment capabilities and alternatives. Bath Iron Works Producibility Assurance Program has simplified design as one of its major objectives.

As an example of the Simplify Design category we will look at the cast in place concrete walls at the Telephone Exchange Building. The cast in place concrete walls designed for the Telephone Exchange Building were designed to be placed in one monolithic pour. While planning the work the contractor determined that they would be more easily constructed if the walls could be placed in two different vertical sections. The quality of the placed concrete could also be better guaranteed if two placements were used. The contractor proposed the design change which called for a horizontal construction joint. The architect and engineer approved the change and made the decision about the location of the construction joint so that it would not affect the aesthetic quality of the wall.

Standardization

Standardization of components in a system or throughout a building increase constructibility by taking advantage of learning curve efficiencies, volume purchase discounts, and simplified materials procurement and management from fewer differing materials. Both the designer and the constructor can get into difficulties caused by the requirements of numerous variations of a component.

The ASWOC design specified ten different types of ceilings throughout the building. In one case the contractor found himself with not enough of one of the types, and when he went to order more, the style had been discontinued and a new type had to be chosen. For some of the bathroom/shower ceilings, the designer had specified a metal ceiling, but did not specify aluminum. A change order to the contract was required to prevent installation of a steel ceiling that would have rusted in the humid atmosphere of a bathroom.

The many ceiling types also proved to cause extra work in that each of the different types of ceilings had to be submitted for approval by the contractor and then approved by the Navy. This in itself was quite an effort since copies of each submittal are distributed to five separate parties. Even after construction, the many ceilings cause extra work because

maintenance stock for each ceiling type must also be handled and stored. Standardization of the ceiling types could have eased the logistics and prevented some of the problems without great sacrifice to aesthetic quality.

Module Engineering/Preassembly Scoping

This category refers to the opportunity to identify project components or subsystems that may be beneficially constructed or fabricated away from the final workface. Designs can be tailored to facilitate the fabrication, transport, and installation of the modules. The benefits of module engineering and preassembly scoping include improved task productivity, parallel sequencing of activity, increased safety, improved quality control, and a reduced need for scaffolding. Such design should consider the methods of transport, lifting limitations, delivery route restrictions, and module to module connections. Modularization should be addressed during the conceptual or schematic phase of design.

As an example of Modularization/Preassembly Scoping we will look again at the precast concrete walls at the PAMT. Although the walls may have been impractical in the sense that local construction conditions were not favorable to precasting, precasting the walls may well have been a

reasonable construction technique. (Here we see the value of economic analysis techniques which can help us decide which issues will prevail as the dominant decision factors.) By precasting the walls at a precasting yard, the designers avoided the requirement for scaffolding. In contrast to the ASWOC which had walls of split-faced-fluted concrete block topped with separate precast concrete fascia panels, the PAMT walls, once finally at the site, were erected very quickly. The same crane that lifted the ASWOC fascia panels into place was used to lift the whole wall panel at the PAMT. The need for the labor intensive and time consuming masonry work that the ASWOC walls required was eliminated by the use of the precasting technique.

It is interesting to note that both buildings experienced problems related to delays in "closing in" the building and the extreme winter weather conditions in Maine. One could always argue that the problems on both buildings were not inherent in the design, but caused by a general contractor who was inexperienced with building construction.[39]

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[39] Both buildings were constructed by Reed & Reed of Woolwich, Maine. Although Reed & Reed had extensive construction experience in building bridges and other heavy industrial concrete construction, these were the first buildings which they attempted to build. Interestingly, both buildings were also designed by the same designer, Webster/Baldwin/Day/Rohman/Czarniecki of Bangor, Maine.

Accessibility

The accessibility of manpower, material and equipment during construction can be promoted or hindered by the design. Poor accessibility results in delays in progress, slowed productivity, and increased damage to completed work. Designers should have guidelines for minimum spacing of project elements. Well defined access lanes and clear spaces for pieces of equipment should be designated. Designers should also consider methods of transport and erection, construction equipment sizes and needed clearances. It is important to recognize potential congested construction activities that are sequenced in parallel and that are in close proximity to each other.

The design for the ASWOC had a potential accessibility problem which involved an uninterrupted power supply (UPS) unit which was to be supplied by the Navy and installed by the contractor. As it turned out, the Navy was not able to supply this large unit in time for it to be placed in its space before the walls and ceilings were placed. One reason for this was that the Navy had decided to provide a different capacity unit than originally planned. Construction of the space proceeded, however, ordering of the final UPS unit was delayed until a mock-up of the desired unit was built by the contractor under a contract change order to check its

accessibility. The mock-up was then maneuvered into the space through the now existing doorways. Luckily the wood framed mock-up fit through all of the openings, and its accessibility was verified. The unit was then ordered.

Accessibility is one of the issues in which 3D computer modelling systems can be of help. During the Bechtel lecture at MIT[40], Mr Killen described how Bechtel was utilizing computerized simulation models to plan work flows and logistics. They have been able to identify bottlenecks and potential accessibility problems during the design phase so that either the design can be altered or different construction techniques can be planned for.

Adverse Weather

If the building site is in an area where extremes in temperature or weather are normally, or expected to be experienced, the designer should be sensitive to how such adverse weather will affect the construction of what is designed. One common problem is mud, and the designer should investigate ways in which its effects can be minimized. In cold climates, quality sensitive work conducted outdoors should be minimized. The constructibility challenges of

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[40] Timothy S. Killen, lecture at M.I.T. in March, 1988.

weather include limited scheduling windows, site access limitations, and quality control concerns.

One example of weather problems occurred during the construction of the PAMT roof system. The foam insulation was delivered on the site and stored on the roof deck, in piles, by the roofing subcontractor. Before the insulation could be installed, rainstorms soaked some of the insulation which was not adequately protected. Fortunately the designers had considered the weather. The roofing specifications required that the insulation be protected against the weather, and stated that no insulation that had been exposed to rain could be installed. (Insulation loses much of its thermal resistance when it gets wet and it can never be thoroughly dried out.) The roofing subcontractor was forced to remove approximately 20% of the insulation from the site and provide other, unexposed insulation.

The ASWOC project had a weather related change involving the timing of the construction of a new parking lot. The contract called for construction of the parking lot in the third phase of the project, which was after the completion of the new building. The contractor realized that the parking lot area would be a perfect staging area for his construction trailors and material storage trailors. However, he realized that unpaved, the area would be too muddy for his purposes. The

contractor subsequently asked for and received permission to construct the asphalt paved lot in phase one instead of phase three. The paved lot proved to work perfectly as a staging area.

Specifications/Appropriate Quality

Specifying the appropriate quality of material and construction for the application, and not overly constraining design configurations or the selection of equipment or material, can have measurable effect on a design's constructibility. Improper standards or code-excessive specifications can be costly. Specifications should allow for and encourage cost-effective alternatives. Machine like tolerances, where unnecessary should not be required. The most beneficial tolerance relaxations permit the use of less sophisticated and expensive equipment and procedures.

Of course there are certain areas where quality and tolerance is imperative, namely in structural members and any moisture protective membrane, especially roofs. However it could be that cracks in concrete decks are more acceptable when the floor will be covered with carpet than when they are to be finished with a more brittle surface such as vinyl composition tile. There are usually many opportunities for standard

specifications to be tailored to the benefit of constructibility.

An example of Specifications/Appropropriate Quality can be seen in the standard painting specification used for the ASWOC. The painting specification required <u>all</u> exposed sheet metal to be painted. During construction this requirement was waived for the exposed galvanized ductwork in the mechanical rooms, areas where unpainted exposed ducts are not an eyesore. This enabled other paint work which was required due to other change orders to be acquired at no increased cost to the Navy.

Local Construction

The category of local construction considers the local availability of materials, and expertise in certain types of construction. The example of the precast wall panels at the PAMT described earlier is an example of problems that can be caused by designing or specifying unfamiliar, or uncommon systems.

Although many problems can be avoided by sticking with familiar locally used materials and techniques, the fact that such a practice might stymie the introduction of new and better technologies makes this category of constructibility

one of the more difficult to resolve. Designers should therefore thoroughly investigate the costs and benefits of novel systems. They should always, however, be aware of the strengths and weaknesses in the local construction market, and use this knowledge when making design decisions.

An example of a local construction issue surfaced during the ASWOC project in the form of electromagnetic shielding. The ASWOC contains many computer systems which process highly sensitive information, and the ASWOC building was required to be designed so that the information could not be detected by sensors outside of the building. The designers were directed to shield the whole building, walls, floor, and roof with a continuous membrane of quarter inch steel. All penetrations of the shield had to be specially designed to preclude leakage of any radio frequency data. The specifications required the welded seams of the quarter inch steel plate to be tested and retested to ensure that there were no cracks. This was the first building design in the local area which required such a shield, and local contractors had many questions about it prior to the bid opening.

During a pre-bid conference held by the Navy for the benefit of the contractors, the shield was the major topic of discussion. The local contractors had no experience with the shielding process. By chance, one contractor from California

was present and described the difficulties they were experiencing in building a similarly shielded building for the Air Force in Sunnyvale, California. He described how the fluctuations in the daily temperature caused the steel plates to buckle and the welded seams to fail. He also described a $2 Million change order that was required because of the problems encountered while constructing the shield as designed. He warned the Navy and the designers that the ASWOC design had the same problems.

The contract solicitation was subsequently cancelled as the Navy investigated the problems and came up with a different method of providing the security for the secret data. However, the construction documents had to be completely re-done to eliminate all of the shielding requirements. The re-design of course cost the Navy much less than if they had attempted to build the design. The Navy was lucky that a contractor with that specific construction knowledge had informed them of the problem before a construction contract was awarded.

Adequate Time

All construction contracts require the constructor to complete the work described in the drawings and specifications in a certain amount of time. In all Navy construction contracts,

there is also a clause called Liquidated Damages which assigns a cost to each day beyond the official completion date that the work remains incomplete. The category of Adequate Time refers to the fairness, practicality, and cost of allowing a construction period to be too long, or not allowing enough time.

The effects of specifying too short of a period for construction include a premium for quick performance, problems caused by not having enough time to plan properly, contractors submitting bogus claims in order to get extra time for completion so as to avoid having to pay the liquidated damages, unrealistic schedules which can make related planning meaningless, and bad feelings from the owner who finds he cannot occupy the building when he expected.

Too short of a construction period can also limit the competition during bidding. This is especially true in an area that is experiencing a surge in construction activity. If a construction company is busy elsewhere, it may not have the ability to take on more work within the time frame that a contract requires. Busy contractors will probably not bid on projects with tight schedules. A good example of this phenomenon was the single bid submitted for the Auto Hobby Shop. The contract solicitation required the facility to be constructed immediately during a time of heavy demand for

construction in New England. Not only was there only one bid, but the bid was 25% above the Navy's original estimated cost. If the Navy had recognized the market situation it could have increased the time for completion and probably attracted a few more bidders. As it turned out, eighty-five days were added to the contract construction period by different change orders. This extra time, if included in the original solicitation, could have enabled the project to be worked into other contractors' schedules, and possibly reduced the cost due to the increased competition.

On the other hand, allowing too much time for completion can cause needless financial losses. This occurs when a contractor could have constructed the building in a shorter time, but since he doesn't have to, he draws out the work, using the total amount of time allowed. By doing this a contractor can perform other projects which may be more demanding of his resources. Allowing too much time not only takes the contractor's focus off of your project, it effectively is tying up your money for a longer period of time than is required. On a large construction loan this may increase loan amount guarantee fees. An unnecessary delay in completion can also prevent an owner from opening a money making establishment, thus precluding any profits that potentially could have been made during that time period.

When setting the time for completion in a construction contract, a designer must therefore be aware of the factors that can affect the construction schedule. These factors include long lead time materials or equipment required by the design, the local construction market, and the owners expectations and flexibility as concerns the completion date.

Advanced and New Technologies

Probably the most difficult category of constructibility for a designer to optimize has to do with the use of new or advanced technologies. This is true for two reasons. The first is the fact that it is often difficult for a designer to keep abreast of the latest construction materials, equipment, and techniques, which may enable him to optimize his design. The second reason is the liability assumed by designers when they specify or design an untried arrangement, construction sequence, system or material. In a lecture to a class at M.I.T, Dr. Thomas Liu of the Cambridge, Massachusetts geotechnical engineering firm of Haley and Aldrich indicated that the legal liabilities associated with novel or untried designs is the main factor which precludes their use, and slows the introduction and acceptance of beneficial new technologies into the construction industry.

The untested nature of a new material, technique, etc., along with the liabilities that could result from a failure in its early manufacture or application, immediately limit the advanced technology's ability to increase the constructibility of building designs. The use of steel for a building's structural frame is a perfect example. Although the large scale production of steel was possible from the late 1850s, the first wholly steel framed building was not designed and built until 1896.[41] Reinforced concrete has a similar historical lag between its invention and acceptance by designers.

An example of the benefits that can be had from knowing about and using a new technique is the now famous up-down construction employed by Beacon Developers at Rhowes Wharf, 75 State Street, and 125 Summit Street, all in Boston, Massachusetts.[42] According to Beacon Developers this technique has saved them much time and money in these building projects. One must ask then, why this technique is not employed more widely in the United States? Is it mainly because the geotechnical design firm of Haley and Aldrich is the only one capable or knowledgeable about the requirements

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[41] James Sutherland, "Developments of the Use of Materials in Structures," in The Great Engineers, ed. Derek Walker (London: St. Martin's Press,1987), pp. 108-118.

[42] Herb Lass and Susan Browne, "Pioneering Earthy Solutions," ENR (January 14, 1988).

of the technique to design for it? How much time and money could be saved if the technique was used at every opportunity?

Up-down construction is just one example of the opportunities to increase the constructibility of buildings by designing for new construction techniques, specifying new materials, or investigating existing conditions with the most technically advanced equipment. Such new technologies can only be incorporated into a design by or with the approval of the designers. Designers must first be aware of the new technologies and then be convinced of their reliability and effectiveness. Designers need a tool that can help them recognize opportunities to use the new technologies. Such a tool would help increase the constructibility of building designs.

Correctness Categories

Missing Requirements

A missing requirement is simply a component or system which is required to make the building totally functional, operable, or usable by the owner, that is not described or required by the design documents. This category does not include items that

the owner thinks of <u>after</u> the design is complete. Rather, the items under this category are those that the designers forgot to include, did not realize needed to be included, or that the owner forgot to request or assumed the designer would include.

Missing requirements can be caused by poor design coordination. For instance, the mechanical designer may not totally coordinate his power requirements with the electrical designer, causing fans or pumps to be shown and required on the mechanical drawings, but no associated accomodation of their power requirements shown on the electrical drawings. Another cause for missing requirements is poor communication of the needs of the owner/occupants to the designers during design. An example of this from the ASWOC project is the requirement for plumbing, drainage, and ductwork for the installation of a sonic cleaner, a unit that cleans parts of communications equipment. The Navy forgot to tell the designers that this equipment would be installed in a certain room, and therefore the designers did not provide the required utilities in that room, or even in that area of the building. The utilities will have to be provided by a change orders to the design and construction contracts.

New Requirements

New Requirements are items required to be provided in the building that the owner doesn't know of until <u>after</u> the design is completed and construction has begun. When an item under this category requires a change to the construction contract, it does not mean that the design was incorrect, only uncontrollably deficient. New requirements come under constructibility issues because they always have an impact on the construction of a building.

An example of the New Requirements category is the additional work required to accommodate computer hardware for a new base-wide supply information system at the PAMT. Subsequent to the design and the beginning of construction of the PAMT, the Navy purchased a large computer system for the Naval Air Station, whose components were to be distributed in different buildings throughout the station. The PAMT was selected to be one of these buildings, requiring it to be altered before it was even completed, so its electrical and HVAC systems could support the new computer hardware.

As a result of the requirement, modifications to the design and construction contracts[43] were made. The designers modified the design, which was then given to the contractor in

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[43] Modification #6 to the PAMT Construction Contract

the form of a request for proposal to construct the design. A modification to the construction contract was then negotiated at a cost of $50,000.00 and a time extension of 103 days. This change order is a good example of the high cost of significant changes that are made late in the project.

Inoperable/Unfeasible Design

The category of Inoperable/Unfeasible Design covers all design that, when constructed, is unable to carry out its intended purpose. This category covers design deficiencies in the structural, mechanical, or electrical load capacities of systems, subsystems, or components. (A separate category covers designs which are operable but unfeasible due to code or regulation deficiencies.) Items under this category may be caused by errors of calculation, design phase changes not coordinated and considered throughout all systems, and simply a faulty design process or one which does not consider all necessary parameters.

Sometimes the faulty design is discovered prior to the construction of the system, but many times the problem is discovered when the system is constructed and fails to perform. An example of an Inoperable/Unfeasible Design occurred at the ASWOC involving a cantilevered roof overhang.

The overhang was framed with structural steel and supported a reinforced concrete roof slab and a precast concrete fascia. When the precast fascia panel was attached to the steel, the framing quickly deflected by as much as six inches off of level. A brace post was brought in to support the overhang until the structural engineer could design a fix. The engineer designed some extra bracing for the cantilevered overhang to eliminate the deflection, and the construction contract was modified[44] to provide the installation of the brace.

A mechanical example of inoperable/unfeasible design occurred at the ASWOC and involved a suite of five rooms that were to be specially constructed for sound isolation. The architect correctly specified special sound seals around the doors between the rooms in this area, but failed to notify the mechanical engineer. The mechanical engineer had supplied air to each of the five rooms but designed the system such that air would be exhausted through an intake in only the central room of the suite. He assumed that the air from all the rooms would move freely from room to room through open doors or beneath and around closed doors. Since the doors in the suite were tightly sealed and always kept closed, it turned out that there was no way for the air to be exhausted from four of the rooms. The fix for this situation was designed by the

[44] Modification #23 to the ASWOC Construction Contract.

mechanical engineer and consisted in sound absorbing, offset wall louvers which allowed the air to move from room to room but maintained the required sound isolation barrier. A modification to the construction contract provided for the installation of the wall louvers.

Interference

Interference is a rather famous constructibility problem that manifests itself during the design phase. O'Connor and Tucker[45] found that as a general rework cause, physical interferences are the most common. They list a number of root causes of physical interferences, but they boil down to the difficulty and inability to visualize the three dimensional integrated systems in a two dimensional format. Bechtel[46] and others are beginning to integrate their design process and are designing now in three dimensions. The Bechtel 3D system automatically highlights all interferences on the computer screen. It seems that such a system will catch everything except the interferences caused by uncommunicated and uncoordinated changes, or overlooked systems, subsystems or components.

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[45] James T. O'Connor and Richard L. Tucker, "Industrial Project Constructability Improvement," Journal of Construction Engineering and Management Vol 112 No. 1 (March 1986): pp. 77-79.

[46] Tom Killen M.I.T. lecture, Spring, 1988.

A typical example of interference occurred on the ASWOC project between the ductwork in the intersticial space and the structural steel framing members. The problem was probably caused by an owner requested change in the building height which resulted in the reduction of the vertical space between the finished ceiling and the roof deck. The request came late in the Construction Documents phase of design and apparently the structural engineer was informed and he shortened the columns. The architect took care of the wall details, but no one seems to have informed the mechanical engineer who had already sized his ductwork with a large controlling vertical dimension.[47] Subsequent to the construction of the structural frame and some of the interior walls, but prior to installation of the HVAC ductwork, the contractor discovered that the HVAC ductwork above the ceiling was blocked by the structural framing members of the roof.

As it turned out, the mechanical engineer redesigned the ductwork in consideration of the actual controlling clearances. Luckily the problem was discovered prior to the fabrication of any of the affected ducts. The redesign was performed in time to preclude a delay to the critical path of the construction schedule.

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[47] This assessment is my conjecture based on conversations with various people and knowing the history of the design phase. The engineer has since claimed that he should be reimbursed by the Navy for doing work which should have been done by the mechanical subcontractor.

As a final comment on interferences the following is presented from the O'Connor and Tucker study:

> "Perhaps the one unifying characteristic of these causes of physical interferences is that they all stem from attempts to crash the design schedule. Of course a certain amount of "quick engineering" is inevitable, for it is not uncommon for certain project systems to be, by necessity, the last designed but the first constructed - as with pipe racks. In these cases, rushed review procedures typically follow and physical interferences are likely to occur. However, the attitude of design managers to "get it on paper and they'll take care of it in the field" may well be the primary root cause of physical interferences."[48]

Unforeseeable Conditions

Unforeseeable Conditions are those site related problem conditions, hidden from inspection until construction operations expose them, that require a change to the design or to the expected construction operation. Unforeseeable Conditions are those conditions that could not be noticed, deduced, projected, expected, or implied by other known existing conditions, site surveys or test borings.

This category of constructibility problem is not uncommon, especially in the building system categories of substructure

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[48] O'Connor and Tucker, "Industrial Project Constructability Improvement," p. 79.

and foundations. Other building systems can be affected by unforeseeable conditions such as storms of great magnitude, strikes, material availability problems, coordination difficulties with neighboring owners' operations schedules, and utility outages and scheduled shutdowns.

Some problem conditions will come in the gray area between Unforeseeable Conditions and Unnoticed Existing Conditions. Many law suits have been argued over what was shown in the design documents, what was implied, what should have been expected, and what should have been investigated. Hopefully with the development of new technologies for site investigations[49] the gray areas will be reduced and the litigation record of these conditions will improve.

An example of an Unforeseeable Condition occurred on the Telephone Exchange Building project during the excavation for the wall footings. The contractor found what appeared to be a weak soil condition in the area of the Southeast corner of the building. A soil testing lab was called in to take samples for analysis of the soil to determine its bearing capacity.

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[49] Some research is being done at M.I.T. by Dr. Ken Maser using ground penetrating radar techniques etc.. Also Carlos Nowak is developing an expert system called "NOMAD" which builds a 3D ground profile from information attained from borings. Additionally, Jim Cowell is studying the costs and benefits of the latest investigation techniques and developing a systematic way to determine the optimal level of pre-construction inspection.

The tests resulted in a requirement to remove a pocket of unsuitable soil and replace it with compacted gravel. This requirement became a modification to the construction contract which cost the Navy $4,347.00 and added five days to the construction period.[50]

Unnoticed Existing Conditions

In this category we place problems that could have been avoided by more thorough site evaluation than was performed. Existing conditions in this category are ones that cause a problem but should have been anticipated, checked out, and designed around. Unnoticed Existing Conditions also covers extraneous requirements that should be communicated to the constructor via the construction contract documents, including such things as mandatory delivery routes, restricted access information, noise level restrictions, security requirements, and other limitations on the contractor's activities.

An example of an unnoticed existing condition occurred on the ASWOC project in the form of underground steam pipe designated for removal by the contractor. The steam piping was shown on the removals site plan with a schematic dashed line showing

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[50] Modification #1 to the Telephone Exchange Building Construction Contract.

its approximate location. The designer obviously knew that the steam pipe was old, abandoned, and requiring removal. The constructor found the steam line in the locations shown, but also found that the line was insulated with asbestos, as was almost all steam line installed during the same time period. The removal of asbestos coated pipe is a whole different operation than removing plain pipe. The on site environmental controls are costly and time consuming, the asbestos insulated pipe is disposed of at special dump sites, and the work is performed by a different subcontractor.

Subsequently, a modification to the construction contract was conformed costing the Navy an additional $33,800.00.[51] Although a small portion of the removed pipe did not contain asbestos, most of it did. The designers and the Navy should have been aware that the steam pipe probably had asbestos insulation, and should have checked it to determine the exact situation and prepared the design documents accordingly. If the existing condition had been included in the design documents, a more competitive price may have been attained for the asbestos removal.

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[51] Modification #26 to the ASWOC Construction Contract.

Incorrect Use/Application of Materials

The incorrect use or application of materials in a design can be caused by the designer's lack of familiarity with the material, system or component, or a lack of understanding of how it will connect or perform in combination with other materials, systems or components. During the construction phase these problems are usually noticed by the constructor and brought to the owner's attention. The designer will normally replace the material with one compatible to the situation, but at times insists that the material be tried. Many designers have had to change their minds only after the material is tried and fails to perform.

This category of problems could be seen as designers experimenting with different combinations of materials, which is a good thing. However, the experimenting should not be done in the context of construction contracts, unless this is desired by the owner. Usually there is some lack of understanding of the material performance characteristics when this type of problem occurs.

The Auto Hobby Shop had two good examples of the incorrect use of materials. First, the roof design called for the use of an asphalt coated roof felt layer below an EPDM membrane. The asphalt coated felt is not needed when a rubber membrane roof

material is used. In this case the Navy was able to delete the asphalt coated felt from the contract at a savings of $500.00.[52] The second example concerned a cementitious wall coating. The exterior elevations of the building were primarily split faced fluted concrete masonry units, but the areas around the windows were specified to be plywood coated with a certain cementitious material that was applied as paint would be. The contractor notified the Navy that the cementitious material was not meant to be applied directly to plywood, but the architect demanded that the combination of materials was sufficient as designed. When the finish was applied to the plywood, the wood soaked up the thin carrier medium, and the finished product was unsatisfactory as the contractor had predicted. The application of the material was stopped until a new material suitable for the application could be found. The contractor and the designer worked together, found an appropriate coating, and made the required changes to the design to accommodate the new system. The new system was provided by the contractor through a modification to the construction contract.[53] The requirement for the change in materials cost the Navy $1,108.00 and added 17 days to the construction period.

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[52] Modification #8 to the Auto Hobby Shop Construction Contract.

[53] Modification #15 to the Auto Hobby Shop Construction Contract.

Incorrect Dimensions

Dimensioning is the act of specifying a distance between two objects, or the size of a single object. In a building design, dimensioning is crucial because it is the only information given to the constructors which tells them exactly the designers' desired configuration of building elements. Problems will arise during construction if important dimensions are missing or incorrect.

If a required dimension is missing, the constructor may have to stop work and ask the designer his intent, or he can guess at the designer's intent or preference. Obviously, the first option will slow down the construction process due to the need for further communication. The second option is quite risky for the constructor, and is the cause of much ill feeling between constructor and designer. A third scenario, which is quite often the case, is when the incorrect dimensioning is discovered after the configurations are constructed. If this happens, work usually stops until the designers and constructors can agree on a compromise, or decide to tear out the work and build it again with corrected dimensions.

The ASWOC project had dimensioning problems probably because of the fact that the steel plate shield (discussed earlier) was erased from the design documents when it was determined

that it could not be adequately constructed. The shield had taken up space and appeared in almost every plan, elevation, section and detail. Thus when it was removed, errors in the dimensions were bound to appear.

In one instance during excavation for the foundations, it was found that the exterior dimensions of the building would not close. This caused a delay in the excavation operations while the surveyor and architects corrected the problem. Another instance where the dimensioning did not work out was in the lobby of the building. A hallway was supposed to intersect the lobby such that the hallway's ceiling treatment could continue straight into and through the lobby and terminate directly over the center of the information desk. As it turned out, the dimensions had been off and the ceiling would have not coincided with the center of the desk. In this case, the solution was to put a break in the ceiling treatment before it entered the lobby, and offset its continuation such that it would center on the information desk. The small offset required electrical changes, millwork changes, and sheetrock framing changes. Thus three trades, whose work was performed by three different subcontractors, plus the general contractor, were affected by the problem. Both of the above mentioned problems resulted in modifications to the

construction contract.[54]

Code and Regulation Violations

The Code and Regulation Violations category covers constructibility problems caused by the design or construction not being in conformance with the building codes and government regulations in force at the time and location of the project construction. This type of problem usually surfaces upon inspection of the construction by the persons responsible for the enforcement of the codes and regulations. There is usually no room for compromise when it comes to violations. The problem must be corrected through redesign, and if already constructed, usually through removal and reconstruction.

Navy construction contracts are subject to the Buy American Act, and this law is the source of many problems during the construction phase of projects which come under its veil. There are two generic problems that result from the Buy American Act. First, contractors tend to ignore the requirements of the act and sometimes install foreign made

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[54] Modifications #24 and #45 to the ASWOC Construction Contract.

materials during construction. The Navy is required to make them remove the foreign components and replace them with American made components. The fencing subcontractor on the ASWOC project was forced to take down a large portion of chain link fencing because the components were made in Mexico. The second standard problem is when the designers specify the inclusion of components which are not made in America. Leaded glass, clear wired glass, and self contained control valves, are examples of components not made in America. Usually a roundabout series of transactions must be used to make everything legal if a design contains such components. In the ASWOC for example, clear wired glass used for interior fire rated windows had to be deleted from the construction contract and purchased by the Navy under a supply contract, a purchase method which is not covered by the Buy American Act.

A design can also suffer from life safety and/or environmental protection code violations. The Auto Hobby Shop has such a problem concerning its underground waste oil tank. During the design phase, the Maine State Environmental Code was changed to require buried oil storage tanks to be either double walled or encased in a concrete containment vault. Unfortunately the construction contract documents did not include this requirement. The contractor subsequently submitted and received approval for the installation of a single walled tank without a concrete containment vault. The tank was installed,

as designed and approved, by the contractor. Upon registration of the tank with the state environmental office, it was discovered that the installation did not meet the code. Unfortunately, the tank must now be dug up and reinstalled in accordance with the State's code requirements.[55]

Clarity Categories

Conflicting Plans and Specifications

The construction documents are divided into two types of descriptions, the plans and the specifications. The plans are the familiar blueprints (drawings) of the building's layout (plans), elevations, cross sections, and details. They contain some printed information which helps describe the drawings. The plans are normally drawn on 30" x 40" pieces of tracing paper, and are numbered with an alphanumeric symbol which divides them into the basic building systems. For example, sheets C1 through C6 would hold Civil Engineering drawings which include site configurations, details, roads and walks, and landscaping. The "A" sheets stand for

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[55] The Navy is currently attempting to make the designers pay for the removal and reinstallation of the oil tank, claiming it was the designer's responsibility to design in accordance with all applicable codes. The problem has strained the relationship between the Navy and the designer, who had performed relatively well on the remainder of their work. The project experienced a net change order rate of approximately 2.5%.

Architectural, "E", "P", "S", and "M" for Electrical, Plumbing, Structural, and Mechanical respectively. The different drawings are usually prepared by different people, and quite often by completely different companies.
The specifications are typed documents which are written to describe the quality of materials, as well as installation and performance requirements of components, subsystems, and systems of the building. The specifications are printed on standard letter size paper, and are organized into sixteen divisions which generally correspond to the major building systems. The sixteen divisions are further subdivided into subdivisions which correspond to building subsystems.

Together, the plans and specifications make up the construction documents, and along with the contract-oriented general and special provisions, they comprise the construction contract. At times, however, the plans are not fully coordinated with the specifications, and information provided in each may conflict. For instance the plans may show both supply and return ductwork as being insulated, whereas the specifications for insulation may require that only the supply ducts be insulated. There is usually a standard paragraph in the General Provisions which gives priority to the specifications when a conflict occurs. The presence of this provision is evidence to the fact that conflicts are not uncommon, and can cause both bidding and construction phase

problems.

The ASWOC project had a good example of conflicting plans and specs in the area of doors and door hardware. Essentially there was a different number of doors shown on the plans than called out in the specifications. Also, doors requiring electric cipher locks and alarms were not the same doors in the plans as in the specifications. A large coordination effort was required during construction between the electrical subcontractor, the door and hardware subcontractor, the general contractor, the architect, and the Navy to straighten out the problems. Additionally, the clarification required a modification to the contract which cost the Navy $16,926.00 and 18 more days in the construction period.[56]

Missing Specifications

The Missing Specifications category refers to components, systems, or subsystems called for in the plans, but not described in the specifications. At best a constructor will translate the lack of specifications as a desire by the designer for him to provide the minimum quality item or configuration available. At worst, the contractor will claim

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[56] Modification #39 to the ASWOC Construction Contract.

that since the item was not described in the specifications, there was no way to bid on it so he did not include it in his bid price. In this case, the contractor will expect to be given specifications for the item and to be reimbursed for its cost via a contract modification.

The previously described example of the paint spray booth at the Auto Hobby Shop is a good example of the missing specification problem. Another example occured on the ASWOC project and involved fire extinguishers and extinguisher cabinets. The plans showed the locations of fire extinguishers, but the specifications did not mention them at all. Also, no mention was made of the type or capacity of the extinguishers, and nothing was said about the size or type of extinguisher cabinets that were desired. One detail on the drawing which showed details for millwork showed how the millwork was supposed to frame the extinguisher cabinets.

The outcome of the extinguisher situation at the ASWOC was that the Navy supplied the fire extinguishers and mounting hooks while the contractor agreed to provide blocking in the walls for the hooks and to mount them on the walls. It was shown that there are type specifications for extinguishers and extinguisher cabinets which are normally used when these items are expected to be provided by the contractor. It was also shown that there was no information in the contract documents

by which the contractor could determine the size or types of extinguishers that were required, and he claimed that he was reasonable to not carry any costs for them in his bid price. Another interesting example of a missing specification problem on the ASWOC project involved duplex electrical outlets and boxes which were located in the raised computer flooring. The contractor claimed that since there was no specification for the outlet boxes, he was not supposed to provide them. The Navy claimed that the drawings showed the location, details, and other information about the outlet boxes on the drawings, and ordered the contractor to install them per the drawings. Without any clarification of the requirements for the outlet boxes, the contractor installed the outlet boxes but took his case to the Armed Services Board of Contract Appeals. The Court held in favor of the Navy saying that there was enough information in the drawings for the contractor to estimate and bid on the work, without the need for specifications. The court pointed to the fact that the contractor did satisfactorily install them without any direction other than the original set of drawings.

Unclear Specifications

Although the specifications are supposed to clarify and detail the quality, performance, location, etc. of building

components, subsystems and systems, there are many times when they fail to do this. When specifications are unclear it may be because there is a word or a number missing from the text, there may be two opposing requirements for the same component, they may refer to an outdated or unpublished standard, they may ask the contractor to coordinate the requirements of the specific specification section with another specification section which is not included with the contract, etc., etc.

Specifications are usually prepared late in the design phase of a project, and are often prepared by persons other than the designers. Typically, and especially in Navy construction specifications, a particular project's specifications are based on pre-written master specifications, sometimes called "type specs". There is a master specification for virtually every specification section and subsection. The persons responsible for preparing a project's specifications must first look at the drawings very carefully and then collect all of the applicable type specs for editing. This is the stage where the need for a specification could be overlooked, resulting in a missing specification. (It should be noted that usually the specifications for the major building systems will be prepared by the different system consultants, e.g. the electrical system specifications will be prepared by someone with an electrical background.)

Once all of the type specs are collected, the specification writer will go through each spec section and edit out portions which do not apply to the particular project. He will also fill in blanks with the number, word, or symbol appropriate for the project. The spec writer can add or delete words or sentences, with the whole intent being the tailoring of the type specs to the specific project. Just as a tailor will fit a stock suit to a particular customer, the spec writer will shorten the sleeves and lengthen the pants, take it in a little here and let it out a little there, until the specifications cover the total design without any open seams.

It is in the process of tailoring the specifications that they can become unclear. This can be caused by inexperience (I once had to prepare specifications for a design for a rehabilitation of a cafeteria on a Navy Base, and I had no idea what I was doing), time limitations, coordination lapses, and unfamiliarity with the type specs. Since the type specs are written by others with much design and construction expertise, it may be that one needs both design and construction experience in order to be able to prepare specifications. (Certainly I have personally found this to be true.)

An example of specifications whose intent was not clear occurred on the ASWOC project in specification section 15250:

Ductwork and Accessories. The confusion concerned whether there was a requirement to externally insulate acoustically interior-lined HVAC ducts. The mechanical engineer's assessment of the situation was as follows:

> "Table 2 information is definitely confusing, and one would not be unreasonable to conclude that no additional insulation is required on lined ducts. On the other hand, wording of Paragraph 3.1.3.2 suggests the government wants lined ducts to have the same thermal insulation effect as unlined ducts. If the cross reference had been in paragraph 3.1.3.6, rather than table 2, there would be no doubt that additional duct wrap is required."[57]

When there is a case of specifications being unclear, the ruling is usually made against the party who prepared the specifications, as long as the contractor's interpretation is reasonable. This is the rule of Contra Proferendum, whose argument is that the preparer has the time and responsibility to make the specifications clear, thus it would not be just to hold the contractor responsible for failures due to causes over which he has no control.[58] The duct insulation case described above was resolved in accordance with the contractor's interpretation of the specifications, and it was

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[57] Richard P. Whitney, ASWOC project Mechanical Engineer, letter to LT Dan Berenato, dated November 14, 1986.

[58] Irv Richter and Roy S. Mitchell, Handbook of Construction Law and Claims (Reston, Virginia: Reston Publishing Company, 1982), p. 29. [This book has a good discussion on the problems that can be encountered with specifications, pp. 14 - 30.]

determined that no exterior insulation would be added to the ducts.

Drawing/Specification Location in Documents

Another problem can arise during bidding and construction if the requirements for a component, subsystem or system are not located in their traditional or normal place within the design documents. The problems arise because of the way subcontractors estimate a job and the way the general contractor assembles the bid. (This was described in the first chapter of the thesis.) In essence, if a component or subsystem of a building system (electrical, mechanical, plumbing, structural, etc.) is not shown in the specifications or drawings where such a component or subsystem is usually described, a subcontractor may not notice it and it will not be included in his bid price.

An example of this type of problem occurred on the ASWOC project and involved the bathroom mirrors. The mirrors were shown on the drawings and specified under the Glazing section of the specifications. The subcontractor who bid on the work covered by the Glazing section carried a cost for the mirrors as they were specified in that section. However, under the Miscellaneous Metals section of the specifications there was a

requirement for the mirrors to have metal frames. The subcontractor who bid on miscellaneous metals work assumed that the glazing subcontractor would supply the mirrors with metal frames as a prepared assembly, and therefore did not carry a cost to provide the metal frames separately. As it turned out, the glazing subcontractor did not know of the metal frame requirement, and therefore did no carry the cost of framed mirrors, nor did he supply framed mirrors to the jobsite. Because the metal mirror frames and the mirror glass were specified under separate specification sections, neither of the subcontractors had carried the cost of the metal frames.

Unclear Drawings

Just as specifications can be unclear, drawings can be vague, contradictory, and misleading. Drawings of a particular component, subsystem, or system usually appear more than once and sometimes many times throughout the set of contract drawings. This increases the chances for a particular item to be drawn differently within the same set of drawings.

Drawings of components, subsystems and systems can also be unclear due simply to the difficulty of representing three dimensional objects in two dimensions. An inexperienced

person would be perplexed by the drawings for the head, jamb, and sill details of a window assembly for example. For the proper communication of the designer's intent, both the designer and the constructor must speak and read the same language of drawings and symbols. Both must understand the viewpoint of the drawing, i.e. the direction of the orthographic projection. Also, both must agree on a standard set of symbols and their meanings.

Beyond an agreement on graphic standards, and a mutual understanding of the drawing conventions, is the requirement to be thorough and consistent. This responsibility exists between the designers and constructors, but significantly, exists between the designers themselves as they share their drawings during the design phase to accommodate system design and coordinate system designs. It is essential that all designers work from the latest drawing updates, and that any changes that are made late in the design phase to a specific drawing, are also made to all associated drawings. Failure to update and account for modifications cause inconsistencies and confusion during the bidding and construction phases of a project.

An example of unclear drawings occurred on the ASWOC project in the drawings for the fuel oil pump system. Some drawings showed two pumps, one for each fuel oil day tank. Other

drawings showed four pumps, the two for the day tanks, plus back-up pumps for each. At some point in the design process someone had either decided for or against back-up pumps, but only half of the drawings were ever modified accordingly. In the end it was clear that the contractor could only be held responsible for providing two pumps, as he reasonably assumed that the designer did not intend to require back-up pumps.

Summary

In this chapter we established categories for constructibility problems and opportunities. The generic categories were summed up into the three general categories of practicability, correctness, and clarity. Each category was illustrated with one or more examples from four case study buildings. The categories comprise the issues of constructibility that constructors and construction contract administrators deal with on a daily basis. Designers must be aware of the problems and opportunities which these issues represent, when designing a building's systems, subsystems, and components. Those who are creating tools for design should be aware that these issues must be addressed by the tool <u>if it is to be of practical use</u>. The next chapter will suggest strategies for

effectively addressing the issues of constructibility with the use of new building design technologies.

CHAPTER FOUR - STRATEGIES FOR IMPROVING CONSTRUCTIBILITY

Introduction

Thus far we have investigated the context and nature of constructibility. In this chapter we will present some thoughts on strategies for improving the constructibility of building designs. First we will discuss the location of the responsibility for constructibility, and question the current strategy of the constructibility review. We will propose that the constructibility review is not optimal because it delegates the responsibility to nondesigners who are constrained by time and knowledge capacity. We will argue that constructibility is optimally addressed during the design process by the designers.

If constructibility is most effectively addressed by designers during the design process, designers must be equipped with the knowledge and tools required to carry out their responsibility. This leads us to an investigation of the nature of the design tools of the future, CAD systems and knowledge based expert systems. We will argue that these emerging tools should be configured so as to facilitate the optimization of the constructibility attribute of a design. We will propose some tactics which might be compatible to the problem and the tools. Finally, we will suggest some sources

of constructibility knowledge, and methods by which it can be attained and organized.

Responsibility for a Design's Constructibility

In the Navy and elsewhere, a design's constructibility is primarily the responsibility of the design team, i.e. the architects and engineers who design and prepare the construction documents. However, because constructibility deals primarily with knowledge of construction techniques, equipment, practices, and concerns, designers normally do not readily recognize constructibility as their responsibility. This is because designers are primarily concerned with how the building will look and perform, while construction issues are considered the constructor's problems.

But what all designers must realize is that they are preparing a description of the building for the constructors, and it is this description which inextricably binds them into a relationship with the constructors, and therefore a share in their concerns. As shown in chapter 1, the construction documents prepared by the designers are the basis of almost all construction activity, be it estimating and bidding the work, procuring material and equipment, scheduling work, packaging subcontracts, producing and submitting shop

drawings, or inspection of the work. Try as they might to be able to concentrate only on "design", design professionals will never be able to disassociate themselves or their work from construction activities.

Perhaps the problem is that designers are uncomfortable when it comes to constructibility because they were not trained in construction or have little construction experience. Certainly this is the case for most young designers and it can hardly be avoided unless years are added to the curricula of college programs. Since this is not a feasible alternative, construction knowledge can be gained only through years of experience, asking questions, and learning from mistakes.

The Constructibility Review

As a result of the fact that designers may lack the construction knowledge to fully carry out their responsibility, the Constructibility Review has been incorporated between the design and construction phases of most projects. The reviews are performed by construction managers, construction contract administrators, and others who are involved with construction phase activities. We will briefly describe the Navy's constructibility review program in the next section.

Constructibility Review Programs

Many excellent constructibility review formats and guides have been developed. The Navy has based its constructibility review guidance on the "Redicheck" system developed by William T. Nigro, (See Appendix B) John Snyder has written a guide for constructability reviews[59] for the Navy for the benefit of inexperienced personnel. Integrated design and construction firms such as Badger also have design reviews by the construction division of the company. O'Connor Rusch, and Schulz[60] indicate that many of the member companies of the Construction Industry Institute have formal constructability programs with written guidance. The Navy's constructibility review procedure is probably similar to most and is presented graphically in figure 4.1.

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[59] John L. Snyder, "Guidance for Constructability Reviews of Pre-Final Navy Construction Contract Documents" (Master's Report, University of Florida, 1985).

[60] James T. O'Connor, Stephen E. Rusch, and Martin J. Schulz, "Constructability Concepts for Engineering and Procurement," Journal of Construction Engineering and Management Vol. 113 No. 2 (June 1987): 236-237.

STEP / LOCATION	1	2	3	4	5	6	7	8	9	10	ETC.
System Designer	X								X		
Architect		X						X		X	
Owner's Design Manager			X				X				X
Owner's Construction Manager				X		X					
On-Site Construction Management/ Administrators					X						

Step 1: System Designers prepare drawings and specifications.

Step 2: Architect or lead designer compiles drawings and specifications for all systems and submits them for review.

Step 3: The owner's design manager accepts drawings and specifications for review - distributes a copy to construction management division.

Step 4: Construction management division reviews documents and sends a copy to the field office for review.

Step 5: On-site construction managers review drawings and specifications for constructibility and make comments and suggestions.

Subsequent Steps: The comments and suggestions go back along the same chain until they get to the system designers. The system designers consider the comments and make modifications as they see fit. Replies to all comments go back through the chain to the on-site CMs.

FIGURE 4.1 Constructibility Review Procedure

Figure 4.1 shows that a design must be passed through many hands (taking much precious time) by the time it is reviewed for constructibility and returned to the designers for changes, corrections and additions. Inherent in this standard process is the fact that design decisions are made without the benefit of a constructibility perspective, (i.e. constructibility issues are not considered during the "Appraisal" phase of the fundamental design process described in Chapter 1) and much of the constructibility ends up being forced into the design <u>if</u> there is time. Significant constructibility improvements discovered during a

constructibility review can require a redesign of one or more of the building systems. The comments in constructibility reviews are often taken as attacks on the competence of the designers. Redesign effort is often not undertaken because of designer resistance to criticism from "mere" constructors.

As a result of the constructibility review process, the responsibility of addressing constructibility issues has shifted, in the eyes of many designers, to others. This shift in responsibility has resulted in complications which will be described below.

The Effectiveness of the Constructibility Review

The practice of having construction personnel performing constructibility reviews is naturally subject to the constraints of time and the availability and capabilities of the reviewers. The corrections and changes to the construction documents, as required by the comments and suggestions from the reviews, are subject to the project schedule as well as to the demeanor of the designer concerning his receptivity to critique and suggestion. These factors thus limit the effectiveness of constructibility reviews. If a reviewer has limited time to perform the review, limited knowledge (we all have limited knowledge), and/or limited

access to pertinent information, he cannot be thorough. Some problems may be caught and some opportunities recognized, but not all. An experienced reviewer, if he has limited time, will most likely only check the documents for mistakes that have previously caused him his biggest headaches. Designers who are under pressure to meet submission schedules, may be reticent to redesign portions of the work as might be suggested by review comments, especially if it is even marginally acceptable. If contract solicitation is imminent, suggested changes which involve redesign of multiple systems, will most likely be dismissed as impractical at this phase of design.

Constructibility Tools

Constructibility reviews have been shown to place the responsibility of a design's constructibility on the shoulders of nondesigners, with questionable effectiveness. We would argue that constructibility should be addressed by designers. However, if we do this, we should be willing to offer the tools which they will need to re-assume the responsibility. We will now take a look at the design tools which are emerging as promising applicants for assisting the designer in the area of constructibility.

Computer Aided Design (CAD)

A study by Atkin and Gill[61] indicates that CAD systems are evolving from simple drafting tools to powerful design environments that are suggesting changes to the traditional organizations and methods of building procurement. Integrated CAD systems, the linking of programs to run different applications from the same database are being developed. The idea of a disintegrated model has been offered as a compromise to the fully integrated design system. It is claimed to be suited to the multi-disciplinary organization of the building design team, and allows the systems of the building design to be controlled by individual disciplines. Each designer is then able to be concerned with only the information relevant to his task at hand. Also of particular encouraging developments is an international graphic standards effort, with IGES (Initial Graphics Exchange Specification) vying for domination.

Atkin and Gill conclude that the ultimate CAD system for building design will be of the component based, 3-D modeling variety. They have developed a configuration of an experimental integrated system which is capable of providing information for management purposes, in addition to producing

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[61] Brian L. Atkin and E. Moira Gill, "CAD and Management of Construction Projects," Journal of Construction Engineering and Management Vol. 112 No. 4 (December 1986): 557-565.

drawings. It uses a Relational Database Management System to manipulate an information base containing details of specifications, costs, durations and resources. The RDBMS accepts graphical data input from a CAD system and relates them to their associated nongraphical data. This configuration was based on a system developed by a manufacturer of timber framed buildings. Their CAD system comprised a graphics subsystem with a graphics library that was used to arrange components hierarchically. However there was a dramatic loss of processing speed when even relatively small amounts of nongraphical (attribute) data were accessed. This was overcome by the introduction of the RDBMS to complement the CAD system's own database.

Knowledge Based Expert Systems

Knowledge Based Expert Systems, (KBES), are specially designed computer programs that solve problems, within a certain domain, in the same manner as would a human expert. They are a form of artificial intelligence, and have come to be used in a number of fields and are currently beginning to appear in the design and construction industries.

Sriram[62] describes the development of KBES, and emphasizes that the use of heuristics to narrow down the search for an answer is a main distinguishing factor in human problem solving. The use of heuristics, which are rules of thumb, tricks, strategies, or any device which reduces the search in large problem spaces, is a main factor which sets KBES apart from traditional programs.

KBES are especially suited for problems for which there is no clear algorithmic solution. They have been developed, for instance, in the field of medicine for diagnosis and in the field of engineering for such things as the design of concrete beam and column connections, weld design and selection, and are currently being developed by such firms as Bechtel[63] and Stone and Webster for building design and construction.[64] Many other fields are beginning to develop KBES, and it is clear that this form of artificial intelligence will be in widespread use in the construction industry in a few years.[65]

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[62] D. Sriram, "Knowledge Based Expert Systems: An Overview," in Knowledge Based Expert Systems for Engineering, ed. D. Sriram (draft copy, 1987), p. 2.

[63] Timothy S. Killen, Manager of Engineering and Construction Technologies Research and Development, Bechtel National, Inc., Lecture at M.I.T. in March, 1988.

[64] Charmaine Harris-Stewart, "Artificial Intelligence Gains in Construction," ENR (April 21, 1988): 34-37.

[65] C. William Ibbs, "Future Directions for Computerized Construction Research," Journal of Construction Engineering and Management Vol. 112 No. 3 (September 1986): 326-345.

A New Approach

If our goal is to apply new design technology to the challenge of optimizing constructibility, our first question must be do we just automate the constructibility review process, or do we approach the challenge from a different direction?

Recognizing the limitations of optimizing constructibility via the constructibility review method, and acknowledging the fact that constructibility is an attribute of the design, we propose that the whole concept of the constructibility review needs to be, (and can be), replaced as the primary method by which a design's constructibility is optimized. In light of our understanding of the design process, the construction process, the capabilities of CAD and knowledge based expert systems, and the issues of constructibility, We would propose that the challenge of optimizing constructibility boils down to providing a design environment in which constructibility issues can be conveniently considered and resolved by the designers <u>during</u> the design process.

In the remaining sections of this chapter we will propose a conceptual outline of such an environment and strategies by which constructibility can be optimized. We will propose methods of obtaining, representing, and utilizing constructibility knowledge so that all of the constructibility

issues described in chapter three can be addressed effectively during a project's design phase. We will begin with a discussion of a design environment which would help designers meet the challenge of the responsibility of ensuring the optimal constructibility of their design.

A Design Environment

We know that Knowledge Based Expert Systems for design are being developed to help human designers solve specific building system design problems. The component based configuration of the optimal CAD system described above by Atkin and Gill suggests a marriage between object oriented KBES and a CAD system.

From the above mentioned developments we would conclude that a building design environment will be developed based on a 3-D component based graphic standards. Object oriented knowledge based expert systems for building design as well as construction management will recognize and manipulate the standard graphic components as objects. Expert systems for design will advise on the selection and configuration of objects, while an expert system for scheduling or quantity take-off will interpret the configurations of the objects for their specific purpose. The building object will be

represented hierarchically as an assemblage of building system objects, which are assemblages of subsystem objects, which are assemblages of component objects.

Expert System Design Modules

Knowledge Based Expert System Design Modules seem to be the basic design tools of the future. Ideally they should be able to be connected to a 3D component based CAD graphics package as well as have the ability to advise the designer on the selection and configuration of building systems, subsystems, and components. The way building design is presently successfully organized, i.e. by design discipline, building system, and phase of design as examined in chapter 1, suggests that KBES design advisors should be based on the same organization. Thus you would not create an expert system that attempts to advise on the design of a whole building, but rather only for the use of a single design discipline for a particular building system, at a specific phase of design. Such individual design modules could then be assembled into building system design advisor packages. A graphic description of the proposed organization of KBES design modules, and module packages is shown in figure 4.2 below.

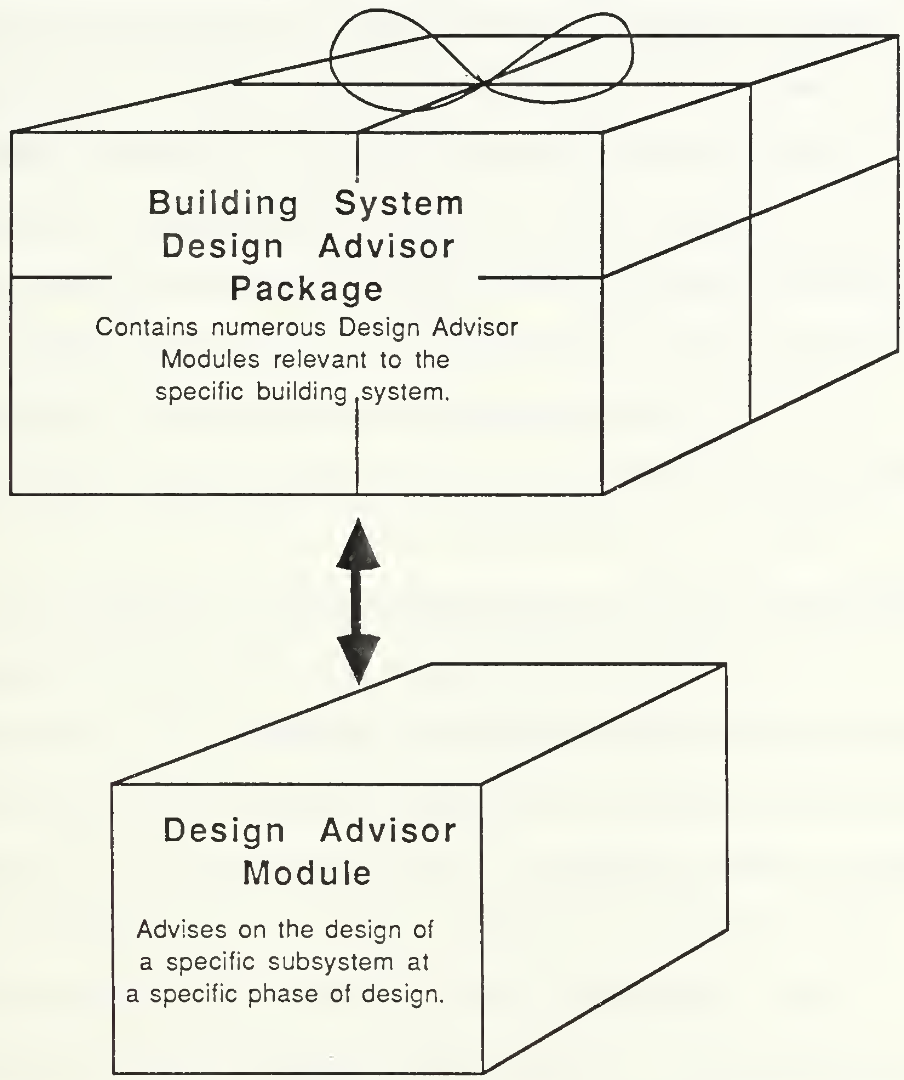

FIGURE 4.2 Organization of KBES Design Modules

Configuring KBES Design Modules for Constructibility

In order to be of practical use, KBES Building System Design Modules must be designed to address each category of the constructibility issues of practicability, correctness, and clarity. They should be able to provide designers with the constructibility knowledge pertinent to the design task at hand. KBES design advisors should lead the human designer through an interactive design session which will ensure that constructibility problems are avoided and that constructibility opportunities are recognized and exploited.

The fact that experts will be consulted to create The KBES design modules will go a long way in ensuring the constructibility of the design produced with these systems. The three dimensional modeling capability inherent when design is performed on a three dimensional, component based format will also in itself have a direct effect in ensuring that some of the constructibility categories are addressed. As mentioned previously, Bechtel's program for three dimensional modeling automatically detects and highlights interferences. The same modeling capability will allow visual simulation of construction operations which could expose accessibility problems early on, and help in the identification of opportunities to adjust the design to make use of optimal construction equipment placements.

Strategies and Tactics for Optimizing Constructibility

In the last few pages we have developed some overall strategies for optimizing the constructibility of a building design. They are:

1. Addressing constructibility issues during the design process;
2. Designing in a three dimensional, component based format; and
3. Utilizing KBES design modules tailored for specific building systems at specific phases of design.

Some tactics which could be used within these overall strategies include design guidelines and checklists, expert selection and sizing, and knowledgeable objects. The concept of these tactics will now be briefly described.

Guidelines and Checklists

The concept of design guidelines and checklists could be utilized as a tactic to address many of the constructibility categories. Such guide/checklists could be the organizational basis of the design process of each KBES design module. Guidelines Publications of Orinda, California has published design guidelines and checklists for the construction

documents phase of architectural drawings.[66] The idea behind guidelines and checklists is that there are so many considerations which must be addressed when designing, that a person cannot be expected to remember all of them. Thus the guide/checklist is first a memory aid. Secondly guide/checklists can provide a record of design decisions, their controlling factors, and the identity of the decision makers. Such a record can prove invaluable during the construction phase of a project when a building system may need to be modified.

The guidelines could include information pertaining to the capabilities of construction tools, equipment, techniques and materials which would limit or enhance the use of certain design elements. A guideline/checklist format for each design module would contain only the appropriate information required for the specific building system and design phase. Thus the designer would not be forced to consider extraneous information. The use of the design module for the subsequent phase of design could be made dependent upon the completion of the checklist from the previous phase. Objects created in a module could be released for transfer to the next module for further refinement when checklists are complete.

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[66] Architectural Working Drawing Checklist I: Commercial, Institutional, and Other Heavy Frame Construction (Orinda, California: Guidelines Publications, 1974).

Expert Selection and Sizing

The concept of Expert Selection is based on the ability of knowledge based expert systems to act as human expert consultants would in a system, subsystem, and component design scenario. An example of such a system would be ROOFUS[67], a system conceived by the author for assistance in the selection of roof systems for buildings. The system envisioned would select the appropriate roof system which consists of roof slope, roof deck, insulation, roofing membrane, and fastening system by considering site characteristics, the climate, elements of the building program, owners and/or designers desires, the structural system of the building, budget and other priorities of the building project.

Each KBES design module would contain similar facilities appropriate to the particular building system and design phase. The designer would be in effect consulting with the system on an interactive basis. The computer would take much less time than a human designer would to analyze the situation and then compare the relative merits of sometimes the hundreds of choices available to a designer. The systems would need to have a competent user interface, an explanation facility, and a knowledge acquisition module through which they could be

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[67] Daniel A. Berenato, "Roofus," a class project for a class at M.I.T. given by D. Sriram, Fall Semester 1987.

kept up to date.[68] A graphics library for components could be part of each KBES design module. A copy of the standard graphics of the components selected by the designer and the expert selector could then be put into the building model database. The use of standard graphics would help with the clarity of the drawings and enable other design or construction management programs to be run off of information in the drawings. Specifications for the selected components could also be transferred from the design module to the building specifications database, ensuring that all components of the design are covered in the specifications.

The concept of expert sizing is similar to expert selection, except that the designer interacts with the KBES to size and configure engineered components. An example of this would be the system being designed by Attilla Banki at MIT which designs beam and column joints for a reinforced concrete structural system. The designer interacts with the KBES to select the appropriate sized rebar, its configuration, development lengths, etc.. Other programs have been designed to size and configure other framing systems and elements. Expert sizing directly addresses the constructibility category of Inoperable/Unfeasible design. Ideally, the sizes and

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[68] All KBES should incorporate the graceful user interface, explanation facility, and knowledge-acquisition module for real world use. The whole KBES design module should have these three characteristics, not just the expert selector portion of the module.

configurations selected with the assistance of a KBES would not only be adequate to support the loads imposed, but optimal in regard to other constructibility considerations, budget limitations, and life cycle costs.

Knowledgeable Objects

The concept of knowledgeable objects is based on the idea that objects in an object oriented paradigm can send messages and perform operations. Thus, an object can be programmed to send a message to the designer if it recognizes itself in a situation that presents a constructibility problem or offers a constructibility opportunity. An example of this would be the case of a mechanical component above a sheetrock ceiling, in that the mechanical object could recognize its need to have an associated ceiling access panel since it is an object that requires maintenance and is above a sheetrock ceiling. It would send a message to the designers to ensure that an access panel is provided in the correct location. This knowledge would be demon-like knowledge and only used if required.

The knowledgeable objects could also be readily updated with new constructibility knowledge as problems in the field are passed back to the designers. This learning process would

help solve the problem associated with the retirement of designers and the loss of their experience. Their experiences of problems and opportunities could be saved within the objects for others to use.

Avoiding Cumbersome Objects

If the design modules are specific to a phase, the objects in each module would only be required to hold constructibility knowledge pertinent to the object in that particular phase. Besides having specific knowledge distributed between design modules, cumbersome objects could be avoided by a requirement for the knowledge to meet a usefulness threshold before it is inserted into an object. Mr. Dan Thompson, author of the Producibility Assurance Manual for Bath Iron Works, indicates that producibility and/or constructibility items should be prioritized by their cost/benefit ratio, with individual items having to have a certain ratio before they are introduced into the producibility/constructibility assurance system.[69] The problem of collecting the constructibility knowledge also presents itself at this point, and will be discussed in the next section of this chapter.

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[69] Interview with Mr. Dan Thompson, of Coastal Group Technology, June 26 and July 7, 1988.

Collecting Constructibility Knowledge

We have thus far presented a strategy by which the constructibility of building designs can be improved. The basis of the strategy is to address constructibility issues during the proper phase of the design process, as opposed to relying on post design reviews. The strategy includes the performance of design in a three dimensional, component based graphics environment. Also proposed is the use of an Object Oriented Knowledge Based Expert System paradigm, supporting the design process with guidelines and checklists, expert selection and sizing, and knowledgeable objects.

In order to create a knowledge based expert system, one of the major tasks is the collection of domain knowledge which can be represented in the format required by the KBES paradigm being used. KBES for design must of course include knowledge of the design process and specific domain knowledge of the system being designed. We have previously argued that constructibility knowledge should be used during building design, and therefore KBES for building design should include constructibility knowledge. Design knowledge can be solicited from designers, but most designers are not the ideal source of constructibility knowledge. I would propose that construction projects should be used as the primary source of constructibility knowledge. A secondary source of

constructibility knowledge, especially knowledge in the constructibility category of Advanced/New Technologies, would be trade journals and research journals covering construction activities.

Construction Projects

The constructibility problems and opportunities of a building construction project are formalized and recorded in change orders, field changes, and claims. The documentation required for these includes reasons and causes, as well as detailed descriptions of the problem, opportunity, or dispute. In essence, the knowledge required to prevent change orders in pending projects is available right in the change order documentation of past projects.

To collect this knowledge, knowledge engineers could analyze change order, field change, and claim documentation in the files of both owners and constructors. Questions which would need to be answered are:

1. What is the constructibility problem or opportunity?
2. In what phase of design should the problem or opportunity have been addressed?
3. What building systems are involved?
4. What knowledge was required to recognize the problem or

opportunity?

5. What knowledge was required to solve the problem or implement the opportunity?

6. What was the cause (constructibility category) of the problem or opportunity?

By finding the answers to these questions, knowledge engineers could then determine the best ways to represent and utilize the knowledge within the design modules. The different strategies and tactics proposed earlier in the chapter could be used or new tactics developed. The knowledge engineer would also be able to place the knowledge in the design module which would be most appropriate. This would ensure that problems and opportunities are addressed as early as possible in order for the project to gain the most benefit.

Constructibility Opportunities in New Technologies

In a similar way, constructibility opportunities inherent in advanced and new technologies should be analyzed and the knowledge represented and utilized within KBES design modules. Advances in the areas of construction materials, equipment, and techniques could be collected from trade journals, scholarly journals and manufacturers. The constructibility knowledge inherent in this information could be represented by

knowledge engineers for the use of designers. The basic KBES design module should have a knowledge acquisition facility which could be used by designers to easily incorporate new techniques, equipment capabilities, and material characteristics, into the modules. Manufacturers could also be taught the format, and could provide users and distributors of the design modules with the information already in the correct format.

Other Sources of Constructibility Knowledge

Besides the above mentioned methods of collecting constructibility knowledge, O'Connor et al have collected constructability ideas through on site voluntary surveys, questionnaires, interviews, preconstruction meeting notes, final project reports, and engineering and construction rework documentation.[70][71] In general, all types of knowledge collection methods should be pursued for the original creation of the KBES design modules. The collection of knowledge by similar methods should then be pursued by the users of the

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[70] James T. O'Connor , Mark A. Larimore, and Richard L. Tucker, "Collecting Constructability Improvement Ideas," Journal of Construction Engineering and Management Vol. 112, No. 4 (December 1986): 463-475.

[71] James T. O'Connor and Richard L. Tucker, "Industrial Project Constructibility Improvement," Journal of Construction Engineering and Management Vol. 112, No. 1 (March 1986): 69-82.

systems according to the philosophy of "never ending improvement".

Organizing Constructibility Knowledge

As constructibility knowledge for use in KBES design modules is collected, it would most advantageously be organized by constructibility category, phase of design, and building system. When analyzing additive, deductive, and value engineering change orders and claims, the costs and benefits associated with the item should also be collected. If the information is organized in this way, it may become apparent where problems are most likely to occur and where opportunities are most likely to be found. The costs and benefits data would also give the knowledge engineer an idea of where to concentrate his knowledge collection efforts.

Ideally, constructibility knowledge should be collected also according to building type. Different building types will most likely have different constructibility profiles. Such profiles would also give the knowledge engineer direction as he developed strategies and tactics with which to optimize the constructibility of the completed design.

Summary

In this chapter we presented the argument that a building design's constructibility is the responsibility of the designers of the building. We showed that this attribute was not effectively optimized by constructibility reviews and therefore proposed that it should be addressed during each phase of the design process. In light of this conclusion and the fact that many designers do not possess extensive constructibility knowledge, we determined that designers needed a design tool to help them optimize constructibility. We proposed that the tool might be a three dimensional, component based graphic design environment, implemented in an object oriented knowledge based expert system paradigm. The system would be composed of packages of design modules, organized by building system and phase of design. The system would utilize graphic standards which could be recognized and utilized by other construction management programs.

The KBES design modules would lead a designer through the design process with guidelines and checklists and provide expert selection and sizing assistance. By incorporating constructibility knowledge into generic objects to be used by the designer, the objects could possibly recognize when they might, (in conjunction or disjunction with other objects), cause a constructibility problem or present a constructibility

opportunity. By sending messages, the objects could ensure that the problem or opportunity is considered by the designer.

In order to represent and implement constructibility knowledge within the KBES design modules, the knowledge must first be collected by the knowledge engineer. We proposed that an ideal place to look would be the change order, field change, and claim documentation of past building construction projects. Additional sources of constructibility knowledge would be the trade and research journals of the construction industry, as well as questionnaires and other job site surveys. Ideally, the knowledge collected should be organized according to building system, phase of design, and constructibility category. Constructibility profiles of different building types could then be developed and serve as guides to show the knowledge engineer where to concentrate his efforts.

CHAPTER FIVE - CONCLUSIONS AND RECOMMENDATIONS

Summary and Conclusions

It was the purpose of this thesis to respond to the research needs for future computerized construction applications by examining the specific concept of constructibility. We have attempted to illuminate the issues of constructibility for the benefit of knowledge engineers who will be providing these tools.

Our approach has been to examine the nature of the processes and players which take a desire or need of an owner and turn it into the "bricks and mortar" of a finished building structure. This effort was required to establish the context of the concept of constructibility. Once we established a picture in our mind of the context, we were able to examine and try to understand the concept of constructibility itself.

Constructibility is an attribute of a building's design, and is the most important attribute of the design during the construction phase of a building project. Building designs which are deficient in constructibility can severely affect both the monetary and time budgets of building projects. The avoidance of constructibility problems and the recognition and

development of constructibility opportunities should be a significant concern of designers during each phase of the building design process.

In order to gain an understanding of the issues of constructibility, we examined the construction phase of four case study building projects. We developed the three major issues of constructibility and further categorized the generic problems and opportunities of constructibility. We examined actual examples from the case study projects to illustrate each category. Our opinion is that all constructibility problems and opportunities inherent in a building design can fit neatly into one of these generic categories.

In the last section of the thesis we proposed some strategies with which constructibility could be optimized. Our opinion is that the current method of performing constructibility reviews of completed designs is not optimal. Since constructibility is an attribute of design, we propose that constructibility issues be addressed during each phase of the design process by the designers. In order to do this, however, designers will need a tool which will give them ready access to constructibility knowledge.

In light of the current capabilities of computer aided design (CAD) systems and the emergence of knowledge based expert

systems into the field of engineering, we proposed that the overall tool should be a three dimensional, component based, graphic design environment implemented in an object oriented knowledge based expert system paradigm. Tactics to optimize constructibility within this environment include design guidelines and checklists, expert sizing and selection assistants, and knowledgeable objects. The design environment would be the basis of packages of KBES design modules. Each module would assist the designer in the design of a particular building system at a particular phase of design. Finally, the graphics for the system would be based on international graphic standards which would make the building model thus produced accessible by other construction management programs.

In order to collect constructibility knowledge to incorporate into the individual KBES design modules, we propose that the change order, field change, and claim documentation of building projects be analyzed. Constructibility knowledge gained from this analysis should be organized by building system, phase of design, and constructibility category. Knowledge engineers could gain insight into where the problems and opportunities of different building types are concentrated by examining the constructibility profile attained from the mapping of knowledge thus attained and organized. We believe that different constructibility issues will prevail depending on the phase of design and the building system.

Recommendations for Subsequent Research

As suggested by the strategies proposed to optimize the constructibility of building designs, the creation of a generic design environment seems to be called for at this time. Concurrently, the knowledge required to create the KBES design modules should be collected and organized. The other attributes of a building design, for example its maintainability and operability, also should be addressed during design, and therefore the design environment should be amenable to addressing the issues of these other attributes. An investigation into the nature and characteristics of the knowledge of all of the attributes of a building design should be performed to give knowledge engineers an understanding of all of the issues which the design environment must be able to accommodate.

In regard to the creation of the design environment, it seems that all research and development of individual design modules, for any building system and design phase, should be coordinated. Thus the different departments in the schools of engineering and architecture, which are concerned with the design or construction of buildings or building systems, (architecture, planning, civil, mechanical, and electrical engineering), should participate in the effort to develop the design environment. Knowledge and techniques already

developed could be shared, and a prototype system could result from the synergy of the collective ideas.

In Closing

We hope that the context and concept of constructibility has been illuminated, and that the general strategies proposed will prove helpful to knowledge engineers as they create the design tools of the future. In the long run, we trust that designers will be given better tools with which to design, and that superior design will be the result.

APPENDIX A Design Phases

Design Phases[72]

Phase I Pre-Design Services

1. Develop Project Schedule
2. Project Programming
3. Space and Flow Diagrams
4. Budgeting
5. Coordination with Government
6. Cost Feasibility
7. Site Survey and Soils Investigation

Phase II Site Development

1. Analysis and Selection of Project Site
2. Master Planning
3. Detailed Site Studies
4. On-Site and Off-Site Utility Studies

Phase III Schematic Design

-Present various configurations to the owner for its consideration and selection.

-Schematic Diagrams

-Engineering evaluation of building system alternatives

-Preliminary construction cost estimate

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[72] These are the nine phases listed by the American Institute of Architects in which the designers' services may be performed. They are from Scope of Designated Services, AIA Document B162 (1977 ed.). The descriptive notes of the phases are from: Irv Richter and Roy S. Mitchell, Handbook of Construction Law and Claims (Reston, Virginia: Reston Publishing Company, Inc., 1982), pp. 46-54.

Phase IV Design Development

-Engineered building systems are refined and incorporated into the architectural drawings

-The size, form, and appearance of the project are defined by sketches and drawings

-Construction cost estimate is further refined

- Also if requested: Models or renderings, Landscape design, Interior design, Furniture and Fixture design

Phase V Construction Documents

-Detailed project drawings are prepared

-Specifications and General Conditions to the contract are developed

-Bidding information is developed

-Permits or approvals required by the Government in jurisdiction are secured

1. Architectural working drawings
2. Structural working drawings
3. Civil working drawings
4. Mechanical working drawings
5. Electrical working drawings
6. Specialty working drawings

-Construction cost estimate is further refined

Phase VI Bidding and Contract Negotiations

-Prepare bidding documents
-Secure bidders
-Review of bids and proposals
-Negotiations
-Award of contracts

Phase VII Construction Services

1. Periodic observation of the work for compliance with the specifications

2. Monitoring of job progress

3. Interpretation of drawings and specifications

4. Resolution of field problems associated with design

5. Review and approval of contractor requests for partial payment

6. Preparation of change orders

7. Review and negotiation of the fair cost of change orders

8. Review and approval of submissions by the contractor such as shop drawings and sample materials

9. Determination (through an inspection at the time) of substantial completion of all or designated portion(s) of the work

10. Preparation of punch list for items yet to be satisfactorily completed

11. Final inspection and acceptance of the project

Phase VIII Post Construction Services

1. Preparation of record drawings

2. Operational Programming

3. Review of warranties

Phase IX Special Services

1. Value Engineering Studies
2. Appraisals
3. Fine Arts Studies
4. Computer Applications
5. Expert Witness Testimony
6. Detailed Material Take-Offs
7. Color Selection

APPENDIX B "Redicheck" Constructibility Review[73]

11-02-82
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WILLIAM T. NIGRO, ARCHITECT
106 PARK STREET, SAINT MARYS, GA 31558

RECOMMENDED PROCEDURES FOR PLAN AND SPECIFICATION CHECKS

1. Preliminary Review
   a) Quickly make an overview of all sheets spending no more than one minute/sheet to become familiar with the project.

2. Specification Check
   a) Check specs for bid items.

3. Plan Check Structural
   a) Verify property line dimensions on site plan against architectural.
   b) Verify building is located behind set back lines.
   c) Verify column lines on structural and architectural.
   d) Verify all column locations are same on structural and architectural.
   e) Verify perimeter slab on structural matches architectural.
   f) Verify all depressed or raised slabs are indicated.
   g) Verify slab elevations.
   h) Verify all foundation piers are identified.
   i) Verify all foundation beams are identified.
   j) Verify roof framing plan column lines and columns against foundation plan column lines and columns.
   k) Verify perimeter roof line against architectural roof plan.
   l) Verify all columns and beams are listed in column and beam schedules.
   m) Verify length of all columns in column schedule.
   n) Verify all sections are properly labeled.
   o) Verify all expansion joint locations against architectural.
   p) Verify dimensions.

4. Plan Check Architectural
   a) Verify all concrete columns and walls against structural.
   b) Verify on site plans that all existing and new work is clearly identified.
   c) Verify building elevations against floor plans. Check in particular roof lines, window and door openings, and expansion joints.
   d) Verify building sections against elevations and plans. Check roof lines, windows, and door locations.
   e) Verify wall sections against architectural building sections and structural.
   f) Verify masonry openings for windows and doors.
   g) Verify expansion joints through building.
   h) Verify partial floor plans against small scale floor plans.
   i) Verify reflected ceiling plan against architectural floor plan to ensure no variance with rooms. Check ceiling materials against finish schedule, check light fixture layout against electrical, check ceiling diffusers/registers against mechanical, check all soffits and locations of vents.

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[73] This was found in the U.S. Naval School, Civil Engineer Corps Officers, "Student Guide for Construction Contract Administration and Management", Port Hueneme, California, 1983.

j) Verify all room finish schedule information including room numbers, names of rooms, finishes and ceiling heights. Look for omissions, duplications, and inconsistencies.
k) Verify all door schedule information including sizes, types, labels, etc. Look for omissions, duplications, and inconsistencies.
l) Verify all rated walls.
m) Verify all cabinets will fit.
n) Verify dimensions.

5. Plan Check Mechanical and Plumbing
a) Verify all new electrical, gas, water, sewer, etc. lines connect to existing.
b) Verify all plumbing fixture locations against architectural. Verify all plumbing fixtures against fixture schedule and/or specs.
c) Verify storm drain system against architectural roof plan. Verify size of all pipes and that all drains are connected. Verify wall chases are provided on architectural to conceal vertical piping.
d) Verify sanitary drain system pipe sizes and all fixtures are connected.
e) Verify HVAC floor plans against architectural.
f) Verify sprinkler heads in all rooms.
g) Verify all sections are identical to architectural/structural.
h) Verify that adequate ceiling height exists at worst case duct intersection.
i) Verify all structural supports required for mechanical equipment are indicated on structural drawings.
j) Verify dampers are indicated at smoke and fire walls.
k) Verify diffusers against architectural reflected ceiling plan.
l) Verify all roof penetrations (ducts, fans, etc.) are indicated on roof plans.
m) Verify all ductwork is sized.
n) Verify all notes.
o) Verify all air conditioning units, heaters, and exhaust fans against architectural roof plans and mechanical schedules.

6. Plan Check Electrical
a) Verify all plans are identical to architectural.
b) Verify all light fixtures against architectural reflected ceiling plan.
c) Verify all major pieces of equipment have electrical connections.
d) Verify location of all panel boards and that they are indicated on the electrical riser diagram.
e) Verify all notes.

7. Plan Check Kitchen/Dietray
a) Verify equipment layout against architectural plans.
b) Verify all equipment is connected to utility systems.

8. Final Plan Check - Make a final plan check with particular emphasis that all bid items are properly identified throughout the architectural, mechanical, electrical and plumbing drawings.

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THE SEVEN MOST COMMON AREAS OF CONCERN

1. Do not indicate thicknesses of finish materials/surfaces when already indicated in specs. A conflict immediately develops if one is changed and the other is not.

2. Finish materials should be indicated on architectural drawings only. Again, for example, if the structural drawings indicate "fluted block" and later the architectural is changed there is a good chance the structural will not be changed.

3. Avoid notes such as "see architectural" or "see structural". Always refer to a specific detail and sheet. Structural supports or raised concrete pads for mechanical equipment should be indicated on structural drawings.

4. Wall Sections. All wall sections should be shown at relative elevation on the same sheet with continuous horizontal reference lines.

5. Keep the number of sheets to a minimum. Plan ahead what will be on each sheet and combine wherever possible. For example architectural, mechanical or electrical site plans and roof plans can often be combined on one sheet. The potential for reduced drafting time, less conflicts, reduced reprodution costs, etc. is tremendous.

6. Avoid match-lines. Plans that are split into portions are difficult to read and check. Numerous design errors have been caused by match-lines. Avoid them at all costs.

7. Keep the same orientation on all plans. If possible, keep the North arrow in the same direction at all times. It is very confusing to have different orientations between architectural, structural, mechanical or electrical plans.

REFERENCES

American Institute of Architects. Scope of Designated Services. AIA Document B162, 1977.

Ames, George. Ames Associates, Winthrop, Maine. Interview, July 1988.

Architectural Working Drawing Checklist I: Commercial, Institutional, and Other Heavy Frame Construction. Orinda, California: Guidelines Publications, 1974.

Atkin, Brian L. and Gill, Moira E. "CAD and Management of Construction Projects." Journal of Construction Engineering and Management Vol. 112 No. 4 (December 1986): 557-565.

Banki, Attilla. Graduate Student at M.I.T., from notes on a research seminar given on the use of expert systems for the design of reinforced concrete joints which is the subject of his study.

Bassias, Frank. Turner Construction, Boston area construction manager. Lecture at M.I.T., May 1988.

Bath Iron Works Corp., Bath, Maine, Producibility Assurance Manual for the Patrol Frigate PF 109 Class, Mod 7, dated April 1, 1975.

Berenato, Daniel A. "Roofus." A class project report for a class given by D. Sriram at M.I.T., Fall Semester 1987.

Bowen, Brian. "B-5 Design and Construction Cost Management." In Architect's Handbook of Professional Practice, edited by The American Institute of Architects. AIA: 1984.

Building Performance Research Unit, Building Performance Essex, England: Applied Science Publishers LTD, 1972.

Cowell, James W, Jr., "The Effects of Inadequate Component Inspection on Facility Repair Projects", Masters Thesis, Civil Engineering, MIT, June 1988.

Czarniecki, Michael. Webster/Baldwin/Day/Rohman/Czarniecki Bangor, Maine. Interviews, June and July 1988.

Department of the Navy, Naval Facilities Engineering Command, Contract N62472-84-C-0355, Auto Hobby Shop, Naval Air Station Brunswick, ME.

Department of the Navy, Naval Facilities Engineering Command, Contract N62472-85-C-0099, Operational Control Center, Naval Air Station Brunswick, ME.

Department of the Navy, Naval Facilities Engineering Command, Contract N62472-84-C-0282, Patrol Aircraft Maintenance Training Building at the Naval Air Station Brunswick, ME.

Department of the Navy, Naval Facilities Engineering Command, Contract N62472-87-C-2530, New Telephone Exchange, Building No. 43, Naval Air Station Brunswick, ME.

Diekmann, James E. and Nelson, Mark C, "Construction Claims: Frequency and Severity." Journal of Construction Engineering and Management Vol. 111 No. 1 (March 1985): 74-81.

Donaldson, Barry, "Stone: New Technology and Design." Architectural Record, July 1987.

Eastman, Charles M., ed. Spacial Synthesis in Computer-Aided Building Design. Essex, England: Applied Science Publishers LTD, 1975.

Gallant, Joseph. Project Manager, NAVFAC Contracts Office, Naval Air Station Brunswick ME. Interviews concerning Contract N62472-84-C-0282, Patrol Aircraft Maintenance Training Building at the Naval Air Station Brunswick, ME.

Grant, Donald P., ed. The Application of Systematic Methods to Designing. Proceedings of DMG3: The Third International Conference of the Design Methods Group. The Design Methods Group, 1975.

Harris-Stewart, Charmaine "Artificial Intelligence Gains in Construction." ENR (April 21, 1988): 34-37.

Ibbs, C. William "Future Directions for Computerized Construction Research." Journal of Construction Engineering and Management Vol. 112 No. 3 (September 1986) 326-345.

Jortberg, Robert F. "Constructability Task Force Report," Transcripts of Presentations CII First Annual Meeting, Keystone, Colo., Aug 6-8, 1985, pp. 147-175.

Kavanagh, Jack T. President of Badger America Inc., Cambridge, Massachusetts. From class notes, M.I.T. Fall, 1987.

Killen, Timothy S. Manager of Engineering and Construction Technologies Research and Development, Bechtel National, Inc., from a lecture at M.I.T., March 1988.

King, Russel "Designing PLans for Constructibility." Journal of Construction Engineering and Management Vol. 113 No. 1 (March 1987) 1-5.

Lass, Herb, and Browne, Susan "Pioneering Earthy Solutions." ENR (January 14, 1988).

Liu, Dr. Thomas. Haley and Aldrich Inc., Cambridge, Massachusetts. Lecture given at M.I.T., Spring 1988.

Markus, T.A., ed. Building Performance. New York: John Wiley and Sons, 1972.

O'Connor, James T., Larimore, Mark A. and Tucker, Richard L. "Collecting Constructability Improvement Ideas." Journal of Construction Engineering and Management Vol. 112 No. 4 (December 1986) 463-475.

O'Connor, James T. "Impacts of Constructability Improvement." Journal of Construction Engineering and Management Vol. 11 No. 4 (December 1985) 404-410.

O'Connor, James T. and Tucker, Richard L. "Industrial Project Constructability Improvement." Journal of Construction Engineering and Management Vol. 112 No. 1 (March 1986) 69-82.

O'Connor, James T., Rusch, Stephen E. and Schulz, Martin J. "Constructability Concepts for Engineering and Procurement." Journal of Construction Engineering and Management Vol. 113 No. 2 (June 1987) 235-248.

Reinhardt, William G. "Aging Highway Gets Load Off Its Feet." ENR, May 5, 1988.

Richter, Irv and Mitchell, Roy S. Handbook of Construction Law & Claims. Reston, Virginia: Reston Publishing Company, Inc., 1982.

Smith, Robert. Naval Facilities Engineering Command, Alexandria, Virginia. Interview, July 1988.

Snyder, John L., "Guidance for Constructability Reviews of Pre-Final Navy Construction Contract Documents", Master's Report, University of Florida, 1985.

Spradlin, Melody. Project Manager, NAVFAC Contracts Office, Naval Air Station Brunswick, ME., interviews concerning Contract N62472-84-C-0355 Auto Hobby Shop, Naval Air Station Brunswick, ME.

Sriram, D., ed. Knowledge Based Expert Systems for Engineering. draft copy used for course text at M.I.T., 1987.

Sturgeon, Thomas. Project Manager, NAVFAC Contracts Office, Naval Air Station Brunswick, ME., interviews concerning Contract N62472-87-C-2530 New Telephone Exchange, Building No. 43, Naval Air Station Brunswick, ME.

Sutherland, James. "Developments of the Use of Materials in Structures." In The Great Engineers, edited by Derek Walker. London: St. Martin's Press, 1987.

Tatum, Clyde B. "Improving Constructibility During Conceptual Planning." Journal of Construction Engineering and Management Vol. 112 No. 2 (June 1987): 191-207.

Thompson, Daniel. Coastal Group Technology, Wiscasset, Maine. Interviews concerning Producibility, May, June, and July 1988.

U.S. Naval School, Civil Engineer Corps Officers, "Student Guide for Construction Contract Administration and Management", Port Hueneme, California, 1983.

Weatherill, Robert. Wadsworth, Boston, Mercer and Weatherill, Portland, ME. Interview June 1988.

Western Division, Naval Facilities Engineering Command, "Constructibility Review Guidance", December 1983.

Whitney, Richard P. Mechanical Systems Engineers Inc., Portland, ME. Interview July 1988.

Whitney, Richard P. Mechanical Systems Engineers Inc., Portland, ME. Letter to LT Dan Berenato, NAVFAC Contracts Office, Naval Air Station Brunswick, ME., concerning Operational Control Center, Naval Air Station Brunswick, ME., 14 November 1986.

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for improving constructi-
bility.